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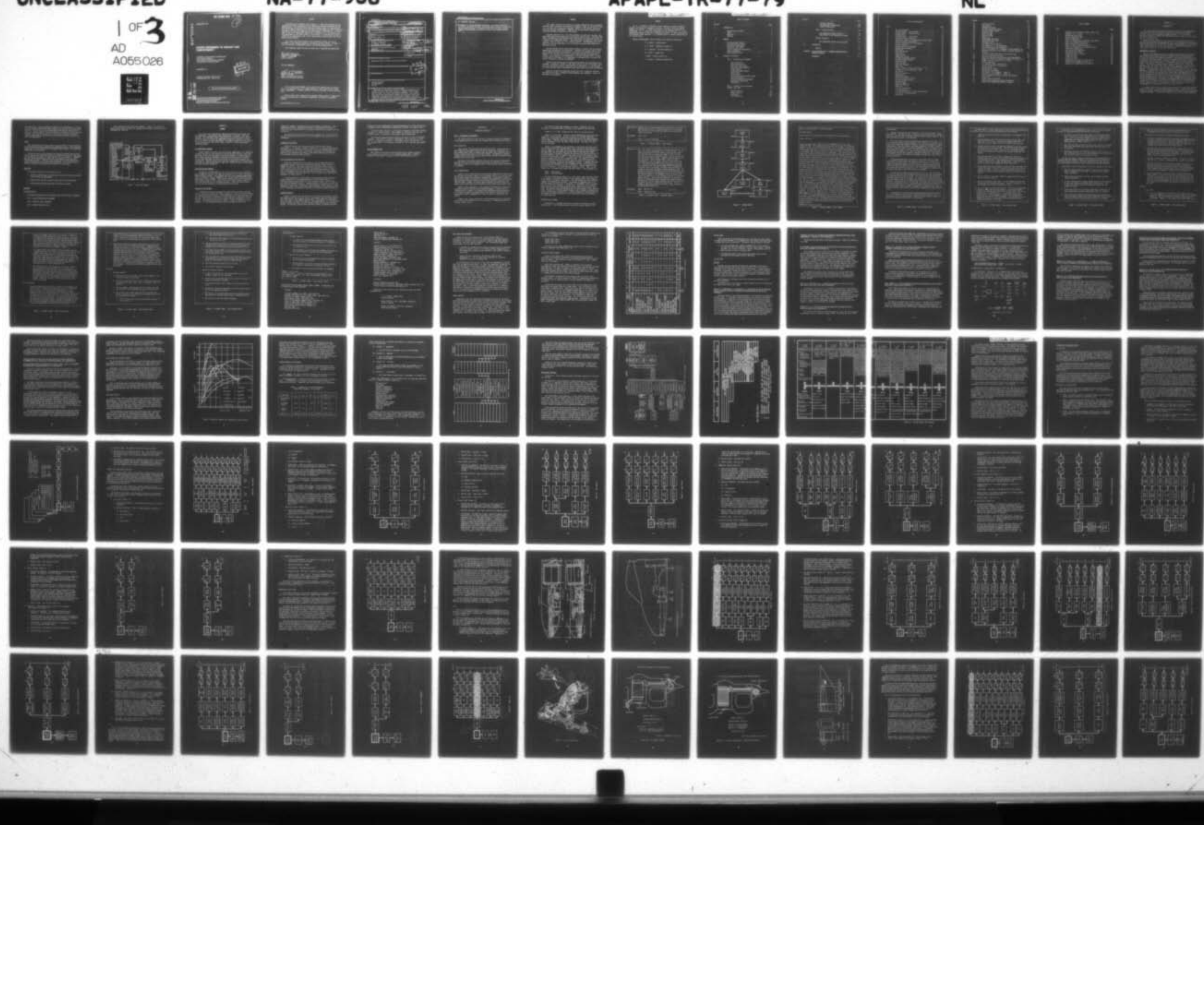

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HAZARD ASSESSMENT OF AIRCRAFT GUN COMPARTMENTS

ROCKWELL INTERNATIONAL CORPORATION
LOS ANGELES DIVISION
LOS ANGELES INTERNATIONAL AIRPORT
LOS ANGELES, CALIFORNIA 90009

DECEMBER 1977

TECHNICAL REPORT AFAPL-TR-77-79
Final Report May 1976 – October 1977

AIR FORCE AERO PROPULSION LABORATORY
AERONAUTICAL SYSTEMS DIVISIONS
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This technical report has been reviewed and is approved for publication.

Robert G. Clodfelter

ROBERT G. CLODFELTER
Project Engineer

FOR THE COMMANDER

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Aircraft gun compartments provide an inherent fire/explosion risk potential because of the common location of flammable fluids, thermal ignition source, and various environmental conditions. This program, while specifically addressing the hazards associated with aircraft gun compartments, investigated other related area of concern. The areas include gun compartment hazard identification, accident/incident reports, historical data on aircraft gun compartment design and evaluation, — over

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development of a hazard assessment methodology, the chemical composition and behavior of typical gun gases, and various types of sensors to detect and measure combustible gases. The results of the study were used to prepare technical design guidance for possible inclusion in the Armament Handbook DH2-5.

SUMMARY

This report contains the results of a study conducted by the Los Angeles Division (LAD) of Rockwell International (Rockwell) under the direction of the U.S. Air Force Aero Propulsion Laboratory (AFAPL) on the hazards associated with aircraft gun compartments. Emphasis was on the hazards caused by gun-firing by internally mounted aircraft cannon.

Accident reports on U.S. Air Force and Navy aircraft were reviewed, and cause-and-result relationships were established statistically. With this data base, a methodology was developed which could assess the potential hazards in a specific gun compartment design. The methodology was applied to two current aircraft, the A-10 and F-15, with credible results. The methodology can be applied to any gun compartment so as to provide a hazard index relative to a baseline aircraft.

The gas emitted from the gun during firing was studied, and its chemical composition and behavior were described. Although the accident reports show few accidents definitely attributable to gun gas, the potential for serious damage to the aircraft and crew due to gas concentration and combustion is evident. Air purging of the compartment is the most effective way to reduce the gas hazard, although if the compartment is designed with a suitable vent ratio, the hazard is reduced considerably.

Sensors which measure gas concentration and define the constituents were reviewed. Ultrasonic, catalytic, and sample bottle are the pre-eminent types, with each exhibiting specific advantages and disadvantages. A test program to better describe sensor performance under operational conditions was defined.

Based on the material generated during the study, suggested revisions and additions to DH2-5, Armament Design Handbook, were prepared. These are included in the appendix.

PREFACE

Mr. R. G. Clodfelter, AFAPL/SFH, project engineer, provided invaluable guidance and assistance throughout the study. William A. Pace was program manager for Rockwell. G. Nadler contributed to the program, especially the methodology. Dr. D. Lifton was responsible for the gas analysis. G. D. Artz managed the program for Rockwell's Rocketdyne Division. I. Lysyj performed the test hardware sensor analysis. W. D. Dotseth and W. K. Thames provided advice in critical areas.

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SECTION I

INTRODUCTION

This final report of the Hazard Assessment of Aircraft Gun Compartments study covers the work performed by Rockwell International, Los Angeles Division, under contract F33615-76-C-2051 from the U.S. Air Force Aero Propulsion Laboratory (AFAPL), Fire Protection Branch, during the time period May 1976 to October 1977.

While the initial intent of the study was to review and assess all the hazards associated with gun compartments, early in the program it was determined that gun-gas hazards are predominate, therefore AFAPL decided to concentrate on them. Accordingly, most of the data analysis is concerned with gun gas, its constituents, behavior, and the resulting hazards.

BACKGROUND AND PROBLEM

Aircraft gun compartments provide an inherent fire/explosion risk potential because of the common location of flammable fluids, thermal ignition sources, and various environmental conditions. High-velocity ventilation air is the major protection measure utilized to minimize the potential hazard, with the required ventilation being a function of many variables such as gun gas composition, surface temperatures, environmental factors, and flammability limits. The design of high-performance aircraft often results in gun compartments that may contain fuel lines, hydraulic components, electrical equipment, and bleed-air lines. They may also be adjacent to fuel tanks. In general, if one component failure (leaking fuel) can result in a fire, the compartment is deemed to be a fire zone, which in turn may lead to the requirement for a fire detection and extinguishing system. Most gun compartments do not contain extinguishing systems since the hot surfaces associated with the gun system (ignition source) exist for only a small percentage of the mission time, and other techniques can be utilized to prevent flammable mixtures from reaching the ignition source. In general, this approach has led to acceptable gun installation with adequate fire protection capabilities for current aircraft designs; however, many of the techniques are not sufficiently characterized and documented for general application for future aircraft.

In recent years, the Air Force has devoted most of its R&D fire protection efforts toward fuel systems and engine/nacelle systems. These are the major areas for aircraft losses due to fires/explosions for both the natural and combat flight environments. Aircraft have, however, been lost due to gun compartment

fires/explosions. Design information related to gun compartments is limited, and each System Project Office (SPO) evolves their own fire protection design criteria. This may lead to misdirected effort and marginal installations. Also, the "lessons learned" may not be generally available for future aircraft programs. This program was initiated in an effort to improve and extend present capabilities as applied to fire prevention/protection of future aircraft gun compartments.

SCOPE

This program was part of an overall Air Force effort to assure effective fire prevention/protection capability for advanced aircraft. This particular program was an initial exploratory development effort related to aircraft gun compartment fire protection.

During the course of the program, the scope was redefined and narrowed. Sixteen separate gun compartment hazards were identified, but the study effort was subsequently confined to a single hazard, fire and explosion. Budgetary and time constraints prohibited extensive investigation of the catalytic combustible gas sensor. Similarly, gun firing tests to verify theoretical results obtained during the study were not pursued. Each of these topics is discussed in detail in the appropriate sections of this report.

OBJECTIVE

The threefold objective of this effort was to:

1. Develop a methodology for assessing the potential hazards asssociated with aircraft gun compartments

2. Establish the required technical input data and test procedures

3. Develop design criteria applicable to military aircraft

APPROACH

TASK DESCRIPTION

The study was divided into three tasks, which were resolved in sequence:

Task 1, Hazard Methodology Development

Task 2, Technical Data Assessment

Task 3, Develop Design Criteria

These tasks were broken down into subtasks. Figure 1 is a task flow diagram, which shows the tasks and subtasks and the order in which they were undertaken and completed.

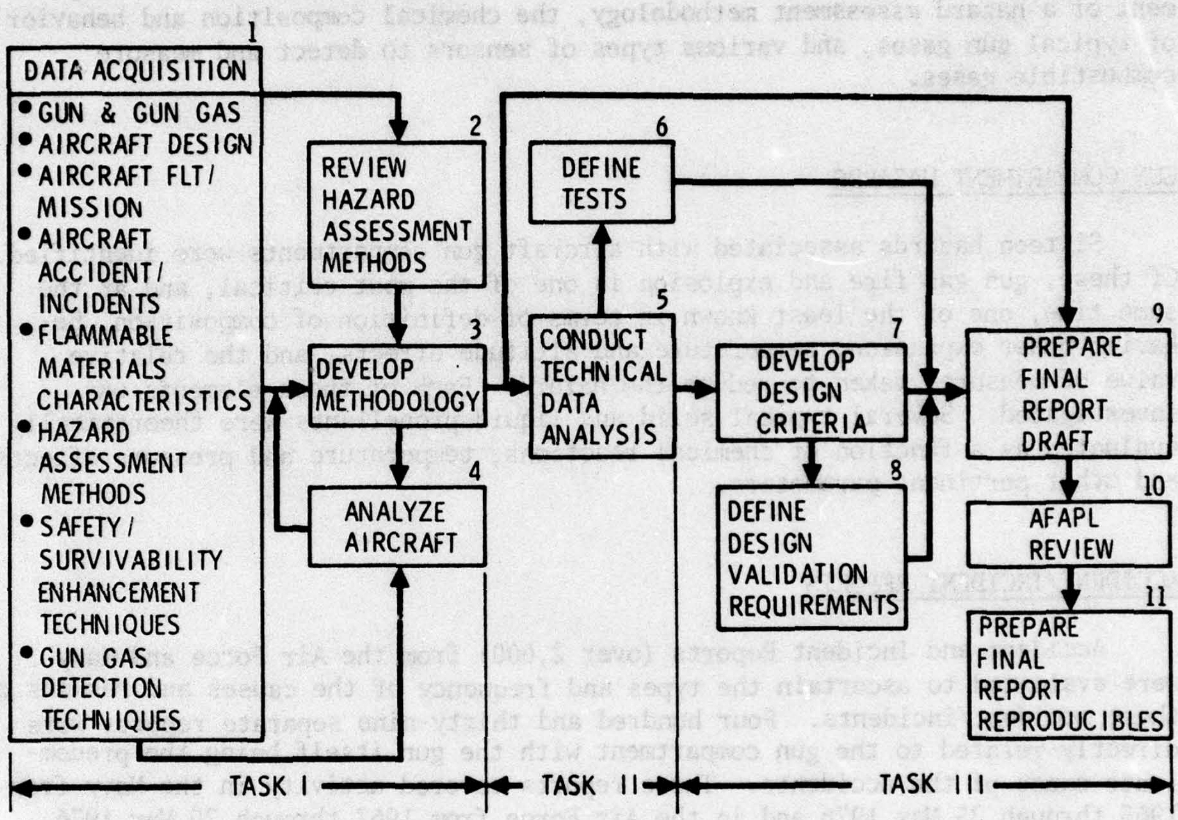


Figure 1. Task flow diagram.

SECTION II

SUMMARY

This study, while specifically addressing the hazards associated with gun compartments, investigated other related areas of concern. The areas included: gun compartment hazard identification, accident/incident reports, historical data on aircraft gun compartment design and evaluation, development of a hazard assessment methodology, the chemical composition and behavior of typical gun gases, and various types of sensors to detect and measure combustible gases.

GUN COMPARTMENT HAZARDS

Sixteen hazards associated with aircraft gun compartments were identified. Of these, gun gas fire and explosion is one of the most critical, and at the same time, one of the least known in terms of definition of composition, behavior under expansion, temperature and altitude effects, and the relative value of measures taken to reduce the hazard. Each of these elements was investigated. Several typical solid and liquid propellants were theoretically evaluated as a function of chemical reactions, temperature and pressure effects, and other pertinent parameters.

ACCIDENT/INCIDENT REPORTS

Accident and Incident Reports (over 2,000) from the Air Force and Navy were evaluated to ascertain the types and frequency of the causes and results of these accident/incidents. Four hundred and thirty-nine separate reports were directly related to the gun compartment with the gun itself being the predominate cause of the accidents. These reports covered activity in the Navy from 1965 through 25 May 1976 and in the Air Force from 1962 through 20 May 1976, which was considered to be a credible data base. There were some problems with the lack of uniformity of reporting detail and clarity.

METHODOLOGY DEVELOPMENT

A methodology has been developed utilizing possible accident cause and result, and thus evaluating the relative chances of a specific event occurring in a particular aircraft design. The methodology can be exercised against any aircraft configuration to determine its hazard rating in comparison with the baseline. The aircraft can be in any stage of design, development, or production. The methodology developed is generic in nature (referred to as the baseline). It was developed using historical accident/incident data,

engineering judgment, and generalized aircraft design configurations. The methodology utilizes a mathematical method of combining possible adverse events in terms of possibility of occurrence and possibility of damage given an occurrence.

The methodology was successfully exercised against the A-10 and the F-15 aircraft design configurations to verify the soundness and completeness of the methodology.

HISTORICAL DATA SURVEY

Historical data on gun carrying aircraft shows two basic design philosophies: (1) design for complete purging, and (2) design the gun bay to withstand specific overpressure and provide a vent ratio (square feet of exit area divided by 100 ft^3 of bay free volume) large enough to withstand the effects of gas combustion and flaming. Most recent aircraft gun bays have been designed using the latter criterion.

GUN GAS COMPOSITION AND BEHAVIOR

Sufficient concentration of gun gases in the gun compartment poses a significant threat of fire and/or explosions that could injure the crew or damage the aircraft. The rapid firing cannon typically used in today's fighter aircraft emit substantial amounts of gas which may fill the gun bay with a mixture of gas and air, and even when substantial amounts of purge air are introduced, can still burn with destructive force. A ready ignition source is contained in the hot gun parts, or in the gas itself, which may be flaming as it leaves the gun.

A rigorous analysis of the behavior of the gun gas emitted by the gun within the gun bay is not feasible because of the uncertain effects of layering, mixing, and pocketing due to the irregular shape of the bay and the installed components within. A general analysis can be made in which the mass rate of flow of air required to bring the gas/air mixture below its Lower Flammability Limit (LFL) can be made using variations of the Le Chatelier equation. A thorough test program is required to validate and expand the analysis.

SENSOR EVALUATION

Sensors to measure the concentration of the gun-gas constituents include the vacuum bottle, the catalytic sensor, spectroscopic, and ultrasonic devices. The vacuum bottle, which samples the gas and is then removed to a laboratory where the sample is measured by means of a mass spectrometer, is, from the data assembled during the study, the most accurate commercially feasible sampling method. The catalytic sensor, which provides a direct, continuous real-time

reading of the gas concentration, has some advantages but is less accurate and, in addition, may be influenced by temperature, altitude, and response time.

The spectroscopic analysis is not feasible onboard an operational aircraft, although it is highly accurate. The equipment is expensive, delicate, and difficult to use. The device utilizes atomic optical properties.

The ultrasonic measuring device measures the speed of sound in different compounds. This device is currently experimental, and little data is available on its commercial feasibility. Preliminary reports indicate that it is very accurate, and it is a promising contender for use in aircraft gun compartments.

DESIGN HANDBOOK DATA

The results of the hazard study have been used to prepare technical design guidance for inclusion in the Armament Handbook DH2-5, Chapter 2, Section 2A, and Chapter 3, Section 3E by the WPAFB handbook section.

SECTION III

TECHNICAL DISCUSSION

TASK 1 - METHODOLOGY DEVELOPMENT

The initial portion of this task was to identify sources of information on gun compartments and to secure all relevant data from applicable sources.

DATA ACQUISITION

Three sources of information were identified early. These were the Air Force Inspection and Safety Center (AFISC) at Norton AFB, California; the Naval Safety Center (NSC) at Norfolk; and the Combat Data Information Center (CDIC) at Wright-Patterson Air Force Base (WPAFB). Subsequently, computer printouts were received from each of these sources and these printouts formed the data base for the study.

The number of accidents/incidents listed in this group was substantial. The AFISC data covered 2,042 events, NSC covered 93, and CDIC covered 65. From these, a total of 439 separate events, which involved the gun compartment, was selected.

DATA INTERPRETATION

Review of the accident/incident data revealed characteristics which, while not affecting the overall impact of the developed statistics on the main theme of the study, nevertheless required interpretation in the detailed portions. Many of the accounts of individual occurrences were fragmentary, with portions that could better define cause and result either deleted or ignored in the published data. Further, it was not always possible to isolate cause and result in an ordered flow from initiation of the problem to the final result.

Added to these ambiguities is the difficulty encountered in evaluating an opinion stated in the data by the reporting agency. Clauses such as "suspect bad lot of ammo," or "probable poor maintenance" appear regularly. It is unwise to ignore a statement made by one close to the incident even though the evidence, fragmentary as it may be, does not substantiate the opinion.

Further, many reports begin with a stated malfunction such as "improper feed" without any reference to the initial cause. A significant number of "unknown" causes result.

The effect of these data problems is to make a judgmental decision necessary in tabulating some of the data in the required simplified form.

Figures 2, 3, 4, and 5 illustrate the variety of the data reports.

Figure 2 is very brief. There are several malfunctions that could have caused the initial problem. One most certainly is a gun-gas explosion. Another was a structural failure of the gun with one or two rounds exploding out of chamber. However, the report states that the M-61 gun system failed and the assessment is that the cause is gun failure. The result is clear; aircraft destroyed.

Figure 3 is an example of the difficulty in isolating cause and result. This has been called the "cascade effect" and a flow chart illustrating it is shown in Figure 4. This chart, which was made from the incident reported in the data shows that the difficulty started from an improperly fed round -- from what cause is not known. Because the round was not seated correctly, it was not extracted. This is actually the result of the first cause but also the cause of yet another problem -- a double feed which occurred when another round was rammed into the first, chambered round. The compressed primer ignited, the round fired out of battery and with the barrel rotated out of the firing position. There were two immediate results - a damaged bolt from firing in the unlocked position, and a damaged aircraft as the projectile tore through the structure in front of the barrel. The gun jammed and the mission was aborted -- the final and most important result. Thus, in this single event, are found seven causes and seven results. The assessment was:

Cause: Feed failure
Result: Aborted mission

The last illustration, Figure 5, is a full report (less sensitive areas) of an accident. The wealth of detail in this report leaves little doubt as to the events, the causes, and results. The investigator has little need for judgment in evaluating the accident. The purpose of including this is to show the amount of detail that is available, for presumably similar accounts are on file for most accidents in recent years. Obviously, this volume of detail could not have been evaluated within the scope of this study. Over 2,000 such accounts would have absorbed much of the resources in data analysis alone. However, the contrast between Figures 2 and 5 vividly illustrates the variety in data detail encountered. It would be helpful to future studies of this nature if better definitions of cause and result could be provided in the abbreviated data.

ADDITIONAL DATA SEARCH

Concurrently, a thorough data search was made for additional relevant subject matter. This involved contacts through the project engineer (PE)

Description:	Napalm strafe. During second pass on strafe part of mission gun bay door came off. Aircraft flamed out. Pilot ejected. Material failure in that M-61 gun system malfunctioned from undetermined cause.
Assessment:	Cause: gun Result: aircraft destroyed

Figure 2. Accident report - brief account.

Description:	F4E. The incident aircraft was on air-to-ground mission. On the first pass 40 rounds were fired without incident. On the second pass, after firing 52 rounds, a loud bang was heard from the nose section and the gun ceased firing. Aircrew then safed the gun and returned to base. Actual rounds fired for both passes was 92 rounds. Damage to the nose gun fairing was discovered in the arm/dearm area. Logistics factor, investigation of the gun system indicates a malfunction due to a double-feed during handoff from the feeder unit to the gun. The bolt extractor lip failed to engage the cartridge rim, resulting in a round being rammed into the chamber but not being fired or extracted. The empty bolt then picked up a second round which was rammed into the chambered round. The chambered round then fired by percussion at the 1030 position, causing the damage to the nose gun blast fairing at that point. The combined action of the chambered round and second round forced the breech bolt to the rear-most position in its tracks, jamming the gun. Based on the evaluation of all available facts, it has been determined that the most probable cause is attributed to a faulty feeder assembly, resulting in the round not being inserted into the bolt extractor lip. This precluded firing and extraction of the first round, resulting in the double-feed malfunction.
Assessment:	Cause: feed failure Result: aborted mission

Figure 3. Accident report - ambiguous report.

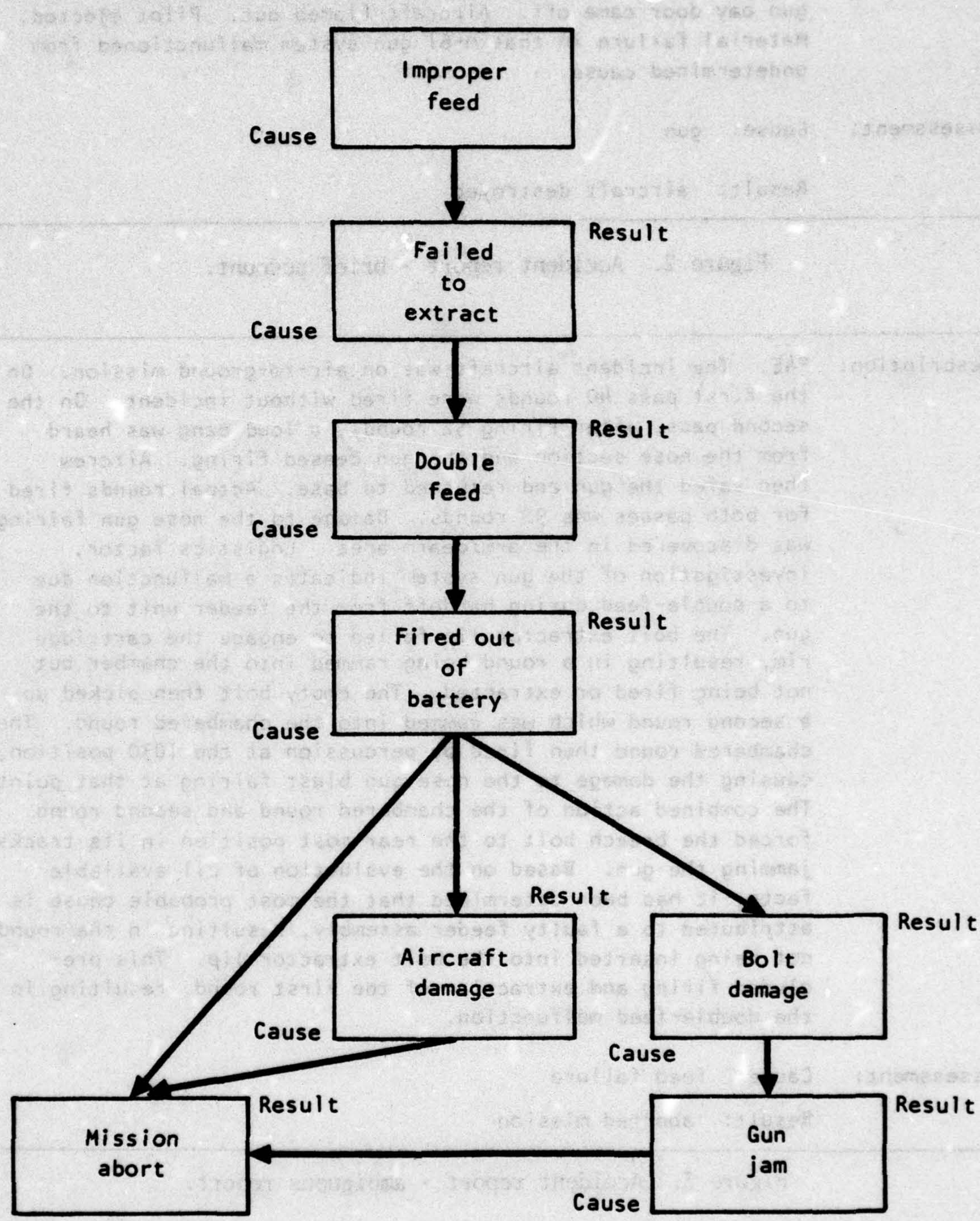


Figure 4. Cascade effect.

Major aircraft accident, aircraft destroyed*

Estimated damage

Pilot injuries, multiple abrasions and contusions to face and legs

History of flight

* __________ a flight of four ____ departed ________ at 1,500 hours EDT. After completing the ____ low level route, the flight proceeded to range. Gun malfunctioned on the first strafe pass. During the recovery ____ noted that the master caution and air turbine motor (ATM) airline overheat lights were illuminated. Shortly thereafter he smelled fumes in the cockpit and informed ____ of his emergency. Just prior to rolling wings level on downwind noted blackish gray smoke coming from forward of the cockpit glare shield and elected to continue his turn towards ____ rolling out at approximately 3,000 feet msl ____ told ____ to go to ____ tower frequency, but ____ replied that he did not want to change channels. When ____ rolled wings level, he adjusted the throttle to approximately 95-percent rpm, selected 100-percent oxygen and noted an illuminated electronic compartment overheat light. ____ then transmitted that the cockpit had filled with more smoke and asked ____ to join on him. As ____ was attempting to join, he noted smoke trailing from the lower middle part of the fuselage. At this time ____ noted the aircraft generator and its associated lights on the caution panel were illuminated. ____ also noted a decrease in pressure on one of the three hydraulic gauges and that he was not holding forward pressure on the stick. He then heard popping sounds coming from the front part of the aircraft and felt the cabin pressure surging. ____ told ____ he was trailing smoke. ____ noted his rpm indication was fluctuating rapidly from idle to military, oil pressure was decreasing, and fuel flow was increasing. By now the smoke in the cockpit had become so dense ____ could not see outside references. ____ reached for the auxiliary canopy jettison handle with his left hand and the right ejection seat leg brace with his right hand. When ____ released the control stick, the stick came smoothly, but rapidly aft. ____ pushed the control stick forward and felt a slight lightness in the seat. He then reached for both leg braces and initiated ejection. The aircraft began to climb. Ejection occurred at 1550 hours, approximately 3,000 to 3,500 feet msl, aircraft 30- to 35-degree nose high, 360 to 380 kias. ____ proceeded back to ____ field. Prior to landing at ____ AFB, ____ established contact with ____ on the ground. ____ was initially aided by two civilians who took him to the crash site. From there he was transported to the ____ regional hospital by military personnel and treated for minor abrasions and contusions received during ejection and parachute landing.

*Sensitive information deleted.

Figure 5. Accident report - full account.

Investigation

Thorough investigations were conducted in the following areas: pilot qualification, crew rest, mission, mission planning, crew briefing, weather, preflight, aircraft and aircrew publications, and maintenance records. None were considered a factor in the accident.

The flight control system was examined and appeared to be normal. The pitch stabilizer power actuator assembly, the flight control servocylinder, pitch series stabilizer autopilot actuator, and the electromechanical linear stabilizer trim control actuator have been shipped to ______ and ______ ALC's for TDR. The pitch stabilizer actuator appeared to be in a condition which would cause the aircraft to climb. The TDR revealed that the flight control servocylinder actuator was in a down and locked condition indicating that the autopilot was off and revealed no component malfunction. The stabilizer trim control actuator was extensively damaged and required a TDR to determine its condition.

A thorough examination of the engine, fuel system, and oil system indicated that these systems were operating normally, no in-flight fire indications could be found in the engine or fuel system. At the time of impact the engine was operating at near military power and was producing sufficient thrust to maintain flight. The rpm calculations noted by the pilot were attributed to erroneous signals to the gauge, the result of fire burning through the wiring and circuitry of the gauge.

The nose section showed intense evidence of a fire. The aft portion of the right nose gear door had departed the aircraft and was found between the range and where the pilot landed. The inside section had pooled and scattered flecks of molten aluminum. The top portion of the strut housing (as the nose gear rests in the wheel well) also had a flow pattern of molten aluminum. The top portion of the nose gear strut yoke, which is an aluminum alloy, was melted and pitted. The pitting could have only occurred by a fire being forced down upon it. Aluminum and aluminum alloys melt at 1,212° F. Several statements from witnesses indicated white smoke was coming from the forward section of the aircraft which further substantiates a nose section fire.

Investigation of the ATM system revealed several sections of the main hot airline piping from the engine to the ATM had small holes or cuts. Laboratory analysis revealed most of these cuts were caused on impact and that this system was not a factor in the accident.

Figure 5. Accident report - full account (cont).

The board began an indepth examination of the M-61 gun with engineering assistance from ________ and determined the following:

1. A 20mm round was fed to the No. 4 breech bolt in a retarded (late) condition.

2. The gun regained control and fired the round, but the right front upper bolt lug on the No. 4 breech bolt assembly broke off on receiving the steel cased round in a retarded (late) condition.

3. The bolt shaft of the No. 3 breech bolt appeared to have been broken upon contact with the locking cam. This was caused by a fragment of the bolt lug from the No. 4 breech bolt which lodged between the No. 3 bolt body and its shaft roller preventing the bolt from locking.

4. The round associated with the No. 3 breech bolt fired in an unlocked condition, forcing the breech bolt rearward and blowing the firing contact cam away. The freed electrical firing lead continued arcing while the trigger was depressed. (Time for firing the No. 3 round to gun stoppage was 25 milliseconds.)

5. As the breech bolt moved rearward it broke the rear rotor gear and impacted the hydraulic gun drive housing with sufficient force to fracture the case. (In the ____ only, the hydraulic gun drive is attached to the back of the rear gun housing in line with the gun rotor.)

6. Utility hydraulic fluid under 3,000 psi escaped from the fractured gun drive and was ignited.

7. The utility hydraulic pump (found in a full demand position) continued supplying fluid to the system. (The utility hydraulic system contains approximately 9 gallons of fluid.)

8. Air to the fire was supplied by bleed air from the gun compartment purge air system and gun ramp purge air. All gun maintenance records were checked and found to be in proper order. The gun was acquired by the ____ TFW on ____. Since then the gun has experienced six jams/stoppages. The gun had fired 520 rounds since the last jam prior to the accident. The wing had a ________ ORI/NEI during ____. Both the munitions maintenance and gun shops received excellent ratings.

Figure 5. Accident report - full account (cont).

Investigation of the background on the_____gun using the dual feed system with steel-cased ammunition revealed the following:

1. Only the_____uses the dual-belt feeder system to supply ammunition to the gun, ______ALC conducted a test on 5 August 1975 of the_____gun system using the M2A2 single-belt feeder and recommended that the single-belt feeder replace the dual, as the M2A2 system has a higher reliability.

2. Data from both the_____TFW,_____and the_____TFG at_____showed that steel-cased ammunition caused faster and more erratic wear on gun parts.

3. Breech bolt assembly, PN 11010157M, presently used in the_______ gun incorporates an electrical safety mechanism so as to preclude the firing of a round in an unlocked condition.

ALC has four specific cases on record where rounds have fired in an unlocked condition because of failure of the locking cam and breech bolt electrical safety interlock. UR's were submitted on the cam, but until now, the breech bolt electrical safety interlock has not been addressed.

Investigation into the progression of the fire revealed the following:

1. When the overheat detection system for the airline to the ATM sensed a temperature of over 400° F, the ATM airline overheat light illuminated.

2. Smoke entered the cockpit initially when overheated bulkhead sealants decomposed.

3. As the fire became more intense, damage occurred to the diaphragm of the cockpit pressure regulator and/or safety valve. This allowed more smoke to enter the cockpit and caused the cabin pressure to surge.

4. Excess heat entered the electronic compartment by radiation and vents causing the electronic compartment light to illuminate.

5. The fire burned through the protective covering on the aircraft electrical cables, causing the aircraft generator failure warning light and the other associated warning lights to illuminate.

Figure 5. Accident report - full account (cont).

6. When the aircraft generator failed, the stab WUC system was disengaged causing the aircraft to be sensitive in pitch.

Investigation of the ejection sequence revealed the following:

1. As the pilot reached for the left leg brace, he grabbed the anti-G suit hose. During ejection the pilot's checklist and/or MXU 163/P clipboard struck his visor. The visor shattered and the pilot received small abrasions and contusions under his right eye. The clipboard was secured only by the velcro strap.

2. The pilot felt that he was tumbling after leaving the aircraft. When the personal parachute deployed, an inversion occurred causing numerous frictional burns in the canopy. The increased aerodynamic airloads on the parachute completely tearing through panels 13 and 27 (including the skirt).

3. The seat kit did not automatically deploy. The seat kit actuator cable failed in tension. Investigation at _____ ALC is continuing.

4. The pilot did not pull the survival kit straps tight because he said this restricted his rotational movement in the cockpit. When the pilot noticed that the survival kit was not deployed, he tried to deploy the kit manually but could not locate the handle or see the kit and assumed it had been lost during ejection.

5. The pilot elected not to make the four-line modification due to canopy damage. He was drifting toward trees and was unsuccessful in trying to steer away from them. He then prepared for a tree landing. He descended through the trees drifting backwards, contacted the ground unexpectedly and fell over onto his survival kit, receiving minor abrasions and contusions to back of his legs and ribs.

Analysis

1. _____ Gun

a. It is not uncommon for the dual-belt feed system in the ______ to deliver rounds to ________________ the gun in a retarded condition. Normally the gun will process a late round with no problems. However, in this case, a late steel-cased round

Figure 5. Accident report - full account (cont).

broke off the upper right front lug of the No. 4 breech bolt. A similar incident occurred at ____ with a ____. The ____ ALC engineer investigated the incident stated that the out-of-time condition also caused wearing on the housing and breech bolts that would not have occurred with brass casings. Generally, when a brass case comes too late to the gun it is deformed by the breech bolt extractor, removing a large piece from the rim and head of the case with no damage to the gun.

b. The present breech bolt assembly electrical safety interlock is accomplished by a small tang or nipple on the end of the stop assembly which shorts out the firing voltage to the roller shaft in the unlocked position. According to the breech bolt improvement study by ____ company, wear on this tang could affect the proper operation of the ____ interlock. The report also states that an improved breech bolt assembly, now under development, virtually eliminates the possibility of accidental firing in the unlocked position.

c. The probable cause of the breech bolt firing when unlocked is that in dynamic (normal) use when the firing cam pin is depressed by the firing cam, the firing pin protrudes beyond the surface of the bolt and makes contact with the relatively soft primer of the 20mm round. The tang on the locking assembly presses against the bolt shaft but, being constructed of extremely hard material, could bounce breaking the circuit to ground. Sufficient voltage is induced to excite the primer and fire the round.

Pilot reactions

1. ____ had stated that he trims for a neutral stick throughout the pattern. While recovering from the strafe pass, ____ would have to trim nose up. The board has concluded that ____, in his anxiety to keep up with the continuing emergencies, probably trimmed the stick to a nose up condition. In addition, the throttle was set at near military causing the aircraft to accelerate after it rolled the aircraft wings level. This acceleration would also give the aircraft a nose up moment. The board concluded that these two conditions caused the stick to come back, as reported by the pilot. Witness statements indicate that the aircraft was flying in a smooth coordinated condition prior to the ejection. The

Figure 5. Accident report - full account (cont).

range officer noted that seconds before the ejection, the aircraft nosed up to about 10 degrees and immediately returned to level flight. Then the aircraft began to climb and the range officer saw a flash which he assumed was the rocket blast of the ejection seat.

2. Approximately 30 seconds elapsed from the time _____ rolled the wings level until he initiated the ejection. Numerous events occurred so rapidly, that the pilot's mental processes and motor response had a difficult time coping. Compounding his predicament, the smoke became so dense that _____ could not see outside references and had difficulty distinguishing cockpit instrument readings. When told he was trailing smoke, _____ released the control stick which moved aft. He then repositioned himself for ejection, pushed the control stick forward, and ejected. The range officer stated that the aircraft started a climb and then leveled off. Although _____ stated that he felt light in the seat, he did not believe the aircraft response was appropriate for the stick movement. The board concluded that _____ decision was timely and correct.

Findings

1. Accident sequence

   a. During _____ first strafe pass, the _____ gun stopped firing while the trigger was depressed.

   b. The front right upper lug of the No. 4 breech bolt broke off on receiving the steel-cased round in a retarded (late) time condition.

   c. The lug fragment lodged between the No. 3 breech bolt body and its shaft roller prevented the _____ bolt from locking.

   d. The firing circuit safety feature within the breech bolt failed to prevent firing voltage from reaching the cartridge for an undetermined reason:

      (1) The firing pin could have protruded beyond the face of the breech bolt.

Figure 5. Accident report - full account (cont).

(2) The locking block could have failed to establish an electrical ground with the rotor.

(3) The contact stop assembly could have bounced an electrical contact with the rotor.

e. The No. 3 breech bolt fired in an unlocked condition forcing the breech bolt rearward with sufficient force to break the hydraulic gun drive housing and ignite the hydraulic fluid.

f. An intense fire developed in the nose section of the aircraft causing the cockpit to fill with smoke and the aircraft generator to come off the line.

g. The pilot decision to eject was further confirmed by increased pitch sensitivity associated with the loss of the stag augs which he interpreted as a loss of flight controls.

h. The pilot ejected sustaining minor injuries.

i. The aircraft crashed and was destroyed.

2. Egress/life support sequence

a. A loop in the anti-G suit hose blocked the pilot's initial attempt to reach the left leg brace.

b. The pilot did not properly adjust his survival kit straps, not secure his MXU-163/P clipboard.

c. The clipboard and/or pilot's checklist struck and broke the visor.

d. The personal parachute experienced an inversion during deployment for an undetermined reason.

e. The survival kit actuator cable broke during parachute deployment and did not actuate the survival kit release mechanism.

f. The survival kit was not manually deployed.

Figure 5. Accident report - full account (cont).

Recommendations

1. Accident sequence

   a. _____guns using the dual-belted feeders be restricted to brass-cased ammunition pending development of a permanent fix.

   b. The M2A2 single-feed ammunition system be installed in the _____model aircraft.

   c. The procurement of a new breech bolt assembly with a positive electrical/mechanical interlock feature be expedited.

2. Egress/life support sequence

   a. The anti-G suit hose interference with the left leg brace during ejection be eliminated.

   b. The adjustment of survival kit straps and proper securing of the clipboard be emphasized during egress training.

   c. Development of anti-inversion modifications be expedited.

Weather: not a factor.
Design deficiency: internal firing circuit safety mechanism______ gun breech bolt assembly; WUC 741Cn; PN 11010157M; federal stock No. 100500-017-8806.

Figure 5. Accident report - full account (concl).

with aircraft system program offices (SPO) at WPAFB. In addition, the following sources were contacted:

Military

Air Force Armament Lab (AFATL), Eglin AFB, Fla.
Armament Development and Test Center (ADTC), Eglin AFB, Fla.
Tactical Air Command, Langley AFB, Va.
Naval Weapons Center, China Lake, Calif.
Naval Air Development Command (NADC), Arlington, Va.
Naval Air Test Center (NATC), Patuxent, R.I.
Center for Naval Analyses, Arlington, Va.
Naval Surface Weapons Center, Dahlgren, Va.
Hill AFB, Utah
McClellan AFB, Calif.

Robins AFB, Ga.
Edwards AFB, Calif.
Shaw AFB, S.C.
Naval Sea Command, Arlington, Va.
Ballistics Research Lab, Aberdeen, Md.

Industry

General Electric Co., Burlington, Vt.
McDonnell Douglas Corp., St. Louis, Mo.
Vought Corp., Dallas, Tex.
Lockheed Aircraft Co., Valencia, Calif.
Control Instruments Corp., Fairfield, N.J.
Hughes Helicopters, Culver City, Calif.
Erdco Eng. Corp., Anderson, Ill.
Bristol Instruments, Waterbury, Conn.
Mine Safety Appliances, No. Hollywood, Calif.
Walter Kidde Co.
Reynolds Aluminum Co., Richmond, Va.
Aerojet Corp., Azusa, Calif.
Northrop, Los Angeles, Calif.
American Gas Association, Arlington, Va.
Southern Calif. Gas Co., Los Angeles, Calif.
Fairchild Republic Corp, Farmingdale, L.I.
Grumman Aerospace Corp, Calverton, N.Y.
General Dynamics, Ft. Worth, Tex
Amron Corp, Waukesha, Wis.

Government

Defense Documentation Center (DDC)
National Aviation Facilities Experimental Center, Alantic City, N.J.
National Bureau of Standards, Washington, D.C.

Additional sources which were not contacted but which have been recommended are:

J. & S. Siegler, London, Eng.,
Catalytic Sensors.

General Monitors, Inc., Costa Mesa, California,
Catalytic Sensors.

Beckman Instruments, Fullerton, California,
Carbon Dioxide Sensors.

DATA ACQUISITION PROBLEMS

During the data acquisition portion of the program, almost all individuals or businesses contacted were cooperative and provided whatever information or literature that was requested. However, some data could not be obtained, even after repeated requests. The following data might have proved useful, but was never received:

1. A standard for combustible gas detectors being written for Instrument Society of America (ISA) by E. M. Nesvig of Erdco Engineering Co. This standard has apparently been approved by the Canadian Standards Association.

2. Details and data concerning a gas detector made by Erdco Engineering Co. This has been used on offshore oil rigs with reportedly a very short response time.

As the data acquisition portion of the study was implemented, it became clear that an important contribution to future gun compartment design/development could be made by establishing a coherent, traceable data bank on all aspects of the subject. It was obvious that the data was fragmented, not well referenced, and in many cases not easily recovered. In tracing the origins of many of the hypotheses in the gas analysis, for example, many of the technical papers which had been used were out of print and considerable effort was required to locate copies. The Los Angeles City Public Library proved to be of inestimable value in this regard. Their Science and Technology Desk *located a Bureau of Mines Technical Paper, for instance, that the Bureau* could not supply from its main office. With these past problems in mind and with the enthusiastic help of many individuals in the military as well as industry, a serious attempt was made to prepare a full list of applicable documents. The references and the bibliography included herein represent the results of that effort. While it would be presumptive to assume that it is complete, nevertheless it represents a thorough search over the period of more than a year. It is hoped that the designers and operators of future gun carrying aircraft will avail themselves of this literature.

COMBAT REPORTS

Subsequent to the data acquisition and analysis portions of the study, additional information on combat losses in Vietnam was received. Three reports were acquired from the Center for Naval Analyses at Arlington, Virginia, which contained much more thorough information on combat losses than had been available. An improvement over previous reports was the inclusion of statements from surviving aircrew personnel where possible. This added an expert viewpoint which was significant in many cases. Unfortunately, only a cursory examination of the contents could be made. At least two probable gun compartment accidents involving gun-gas were found in the initial listings.

It is impossible to predict what number of gun-gas-related accidents could be found if a thorough analysis was made. For possible future review, the reports are as follows:

AD-B017-831L, Part 1
AD-B017-832L, Part 2
AD-B017-833L, Part 3

The title is "U.S. Navy, Marine Corps, and Air Force Fixed-Wing Aircraft Losses in Southeast Asia (1962-1973)", (U).

ACCIDENT/INCIDENT REPORTS

Review of the AFISC, CDIC, and NSC accident/incident reports and tabulation of the findings resulted in the accident/incident frequency matrix shown in Figure 6. The ranking is shown at the bottom as 1, Gun; 2, Ammunition; and 3, Personnel.

While each cause may have a number of subcauses, the overriding requirement to limit study scope and concentrate on gun-gas made the groupings shown desirable. The gun, for example, can have many causes of failure. Among these are part failure, double feed, cookoff, hang fire, or jam. These are grouped together and the product, along with the other causes and results, is a comparative listing of all the events evaluated.

The evaluation was made with first-cause paired with final or most important result. As will be noted, this leads to a significant concentration in categories such as aborted mission, aircraft damaged, and ammunition explosion.

As previously discussed, the concise nature of the computerized reports made precise evaluation difficult in many events. This is reflected in the large number of unknown causes. Where the initial cause of the event could not be precisely determined with reasonable examination, it was placed in the unknown category. While the total number of these unknowns is sizable (116), the results suggest that they would be distributed among the causes in much the same way the others are distributed. It is reasonable to place the 29 unknown jams with gun, feed, and purge. The 19 lost parts might well be placed mainly under the categories of gun and feed. Consequently, the large number of unknown initial causes probably does not significantly affect the matrix values shown.

FINAL RESULT / FIRST CAUSE	GUN	DRIVE	FEED	PURGE	AMMO	A/C STRUCT FAIL	A/C SYS FAIL	PERSON-NEL	UNK	TOTAL
JAM	6		19		35	1		3	29	93
EXPLOSION-AMMO	10		6	1	10			11	16	54
EXPLOSION-GAS	8			1						9
A/C DAMAGED	23		8	1	9	1	1	8	15	66
LOST PART	10				1	2	6	21	19	59
ABORTED MISSION	16	3	6	2	3	1	1	7	11	50
FAILURE TO FIRE	5	1	7		6	1		2	6	28
FIRE					1				1	2
OTHER A/C DAMAGED								1		1
A/C DESTROYED	2		1		1		1		1	6
VALVE LEAK				5						5
INADVERTENT FIRING	3				1		9	6	4	23
GUN DAMAGED	7		3		1				8	19
MALFUNCTION	2		8		3		1	2	5	21
IMPROPER GUN DRIVE OPERATION						1		1	1	3
TOTAL	92	4	58	10	71	7	19	62	116	439
	1				2			3		

Figure 6. Accident/incident frequency.

HAZARD VALUE

After reviewing the accident/incident data and noting the small number of purge failures recorded, it is appropriate to ask whether additional effort to reduce the hazard is worthwhile. The answer could be stated in two ways:

1. It is not necessary for a hazard to happen for it to be critical. The mere fact that the potential exists is reason enough to attempt to reduce it or avoid it entirely. Further, the potential loss is high; aircraft or pilot, or perhaps both.

2. The ambiguous nature of the reports may conceal other serious accidents that have begun with gas combustion.

GUN-GAS DATA

History

Although aircraft incidents involving gun compartment explosions or fires have occasionally been severe enough to cause loss of the aircraft, relatively little attention has been paid to the problem. Design information is limited; no generally recognized criteria exist. As part of the current study, an in-depth survey of existing experience with gun compartment hazards was made. This included a review of published documents, accident/incident reports, and data from equipment suppliers.

Brief summaries of documents which were reviewed are presented in the following paragraphs.

Terminology used in the reports is quoted verbatim and is not necessarily the same as that used in this report.

Horan, J.J., Onderdonk, J.R., and Witkin, E., "Reduction of Gun Gas Explosion Hazard in Combat Aircraft," Aeronautical Engineering Review, March 1952, Reference 1.

Early discussions of the problems appeared in the Aeronautical Engineering Review in 1952. It contained a good description of the gun-gas problem and discussed means of combating it; then concluded that the best way to protect the airplane was to supply air at a high enough flow rate to get the average gun-gas concentration in the compartment rapidly to 50-percent Lower Explosive Level (LEL) or lower. Even with an average concentration at this level, it is possible for pockets to exist above the lower explosive limit. If these should ignite, the resulting pressure rise would remain within acceptable limits. A series of curves was presented showing relationships between allowable pressure rise (in case of explosion), gun gas concentration, and altitude for installation of the M-3 gun. The Naval Air Development Center (NADC) Gun-Gas Detector and its use in determining combustible gas concentrations was described.

"Tentative Criteria for Evaluating the Danger of Explosive Mixtures in Gun Compartments" - ADC-AR-52, 1952, Reference 2.

Essentially the same data as previously discussed. Seems to be almost an exact copy.

R. H. Wright, "Gun Gas Analysis of the XFJ-2B MK-12 20 MM Gun Installation," NA-52-1323, December 1952, Reference 3.

This document reported results of a test program to determine the effect of bleed-air purging on gas concentrations in the gun compartment of the XFJ-2B. Both ground firing tests and flight tests were conducted. Measurements were made during the ground tests using four NADC sniffers and Orsat-type analyses of samples collected in 28 bottles distributed through the compartment. For the flight tests, samples were collected in eight strategically located bottles. The standard Orsat procedure was adjusted to account for H_2 by burning it with some of the CO after the CO_2 removal, with a hot platinum wire in a combustion pipette. The shrinkage of the sample after combustion and the measure of additional CO_2 formed from the combustion of the CO was used to determine the amount of H_2 in the sample.

The approach during the series of tests was to fix any undesirable condition which was identified before proceeding to the next test. Final results indicated that the guns could be fired safely to the operational ceiling of the aircraft and at flight velocities as low as 80 percent of velocity maximum.

Geib, E. R., and Clark, F. E., "Sampling and Analysis of Gun-Gas YF-100A Test Nose", NA-54-439, April 1954, Reference 4.

The purpose of the tests was to determine concentrations of gun-gases in the gun bay during ground-test firing. The purge system used fresh air which was forced, by a large blower, into the purge air inlet scoop inside the engine air duct. Samples of gases from 24 points within the compartment were measured with an Orsat-type apparatus. Two "Fire-eye" detectors were installed to record breech flaming. With flaming, Orsat analysis may indicate that the percent LEL is in the safe range, even though an explosion has already occurred. Results of the measurements indicated that the system was safe enough to proceed with the flight test program.

Edwards, P. R., "F-100A Gun-Gas Purging Flight-Test Program (NA-192)," NA-55-605, August 1955, Reference 5.

The purge system bleeds air from the engine air inlet duct and discharges contaminated purge air overboard through louvers in the gun bay access doors.

Flight-test results were summarized. Measurements and corrective actions to reduce the percent LEL were noted. The purge system maintained LEL levels around 100 percent, although some tests reported values as high as 213 percent in the gun compartment at high altitudes. This was not considered to be critical because, above about 30,000 feet, the pressure developed by the gun gas, if it could ignite, would be very low.

Mount, J. S., and Geib, E. R., "Gun-Gas Purging in Combat Aircraft," Aerospace Engineering, July 1958, Reference 6.

The effects of altitude and exit area on pressures developed in gun compartments due to burning of gun gases were discussed. Fuel concentrations to reach LEL increase with altitude, approximately doubling in value from sea level to 50,000 feet.

Qualitative data were presented from experience with F-86 and F-100 airplanes which were designed to withstand pressure in the gun bay of approximately 5 psig. This pressure would result if the purging air inlet scoops were open during a maximum velocity dive. Above 12,000 feet, combustion pressure would be less than this value. With flaming from the breech, no overpressure problem was experienced to altitudes of 20,000 feet.

Elimination of the explosion hazard can be achieved with a ram-air purging system, according to the authors, if an adequate vent ratio (at least 5) is provided and the flaming characteristics of gun-ammunition combinations are accounted for. They feel there is no need to design for a LEL of 100 percent or less.

Russo, Robert U., "An Investigation of Gun-Gas Concentrations in the F-105B," APCG Study, October 1961, Reference 7.

The F-105B gun was mounted in the nose and not in a separate gun bay. There was a small amount of venting plus an evacuation system incorporating a high velocity airflow nozzle ejector. Residual gas in the nose after firing and evacuation was approximately 1 pound after a 2-second burst at 35,000 feet. This report documented the results of a study to investigate the potential effects of the gas concentration on the safety of the airplane with respect to pressure rise in the compartment due to explosion of the gun gas.

The analysis considered the pressure rise as a function of the amount of gas left in the nose after various burst lengths. A nonflow model was established to define the average concentration in spherical space around the breech and, using perfect gas relationships, the pressure rise resulting from

combustion of the gas in the sphere was computed. Concentration was based on an LEL of 10.5 percent by volume (which could not be checked from the data presented in Table 1 of the report). However, assuming 10.5 percent to be the proper value, an allowable pressure rise was used to compute an allowable firing time.

Although the analytical approach to establish an allowable firing time is generally sound following the initial assumptions of a fixed volume (Calculations 1-3), there are a number of errors. In Calculation 3, for example, the average amount of gun gas in 2.7 cubic feet of mixture at 920° R = 0.888 ft^3. This corresponds to 0.502 ft^3 at 520° R and leads to the mass distribution of the constituents, as shown in Table 2. That is, the mass of gun gas in 2.7 ft^3 is 0.026204 pounds at 920° and 520° R because mass is not affected by changes in temperature, although volume and density are affected by changes in temperature. Therefore, for 1 second of firing at 100 shots per second:

$$\frac{\text{Mass of Generated Gas in Mix}}{\text{Mass of Gas due to Purge Diff}} = \frac{0.0262}{0.380} = 0.07 \text{ seconds} = 7 \text{ Rounds}$$

instead of the 12 rounds shown in Calculation 3.

In Calculation 5, Equation 1 is a misapplication of Le Chatelier's equation in which L, the limit of the mixture of combustible gases, should be computed from the proportions of each combustible gas present in the original mixture, free from air and inert gases. The computation, based on the method outlined in Bureau of Mines Bulletin 503, should be as shown below:

	Vol %		CO_2	N_2	Total	Ratio $\frac{I}{C}$	Limit
CO	50.03		--	4.3	54.33	0.07	12.5
H_2	15.15	7.15	--	6.0	13.15	0.84	8
		8.00	5.03	--	13.03	0.63	6.5
Total	65.18		5.03	10.3	80.51		
H_2O +					(19.49)		
					100.00		

$$\% \text{ LEL} = 100 \left(\frac{54.33}{12.5} + \frac{13.15}{8} + \frac{13.03}{6.5}\right)$$

$$= 100\ (4.35 + 1.64 + 2.00)$$

$$= 800$$

Since the percent LEL is computed with no air or inert gas in the mixture, the statement (on Page 38) that the percent of LEL "for any mixture may be governed by varying V_m (the volume of the gas-air mixture) at a constant V_g (gun-gas volume)" is incorrect. The validity of the derivation of Equation 6 in Calculation 5 is thus open to question.

The analytical results were checked with a test program using a flexible chamber and then correlated with tests in an F-105B nose section. As a result of the analysis and tests, it was concluded that it was safe to fire the M-61 gun mounted in the F-105B in unlimited bursts at any altitude because the pressure rise resulting from combustion of the gun-gas would not exceed allowable limits. This conclusion seems to hold up in spite of the unrealistic analysis, primarily because of the large quantity of vent air which is available.

Dorko, W. D., Taylor, J. K., and Shultz, J. I., "Report of Analysis of Thirty-One Gun-Gas Samples by Mass Spectrometry," NBS, May 1974, Reference 8.

The mol percent compositions of samples of gas taken at five different locations within a test aircraft were determined. Highest percent LEL values were recorded in the vicinity of the breech; other locations showed percent LEL's well below 100.

Mount, J. S., "F-100A and C-Gun-Gas Purging Systems Altitude Effects," NA57-530, April 1957, Reference 9.

Laboratory data, flight-test data, and analytical calculations for the F-100A and C airplanes were examined. Effects of gun-gas characteristics, vent area, structural integrity, and pressure increases due to combustion of the gun-gas were evaluated. Results indicated that, for a medium-rate burning fuel such as gun gas, a vent ratio of 5 is adequate to keep pressure rises in the gun compartment due to combustion from exceeding or approaching the structural limit, even though concentrations were considerably higher than 100 percent of sea-level LEL. It was recommended that the 100 percent sea-level LEL, which has been the criterion for satisfactory purging, be replaced by a more rational set of criteria such as vent area, structural integrity, presence or absence of flaming, and altitude effects on flammability and combustion characteristics.

AFAC-TR-56-49 (U) Air Force Armament Center (Eglin), "Test of the Armament System in the F-100A Aircraft, June 1956, Reference 10.

The aircraft was tested at altitudes from 5,000 to 54,700 feet, air speeds from M = 0.51 to M = 1.12. A total of 200 rounds per gun was loaded and fired in 2-second bursts with 10-15 seconds delay between bursts. There were 10,069 rounds fired. There were 11 stoppages, seven gun stoppages, two feed, one electrical, and one undetermined. Two bursts were delayed because of the purge door failure to open promptly. This was attributed to the low temperature at high altitude.

Gun-bay burning and detonations occurred continually during gun firing; however, the detonations were of low order and did not cause structural damage.

One gas explosion occurred because of an eroded barrel seal which leaked excessive amounts of gun-gas into the bay. The resulting explosion blew the RH gun bay door off.

Heine, B. J., and Bay, A. H., "F-15 20MM Gun/Airframe Ground Test," MDC A2274, June 1973, Reference 11.

The original F-15 gun-gas purge system consisted of a gun compartment ram-air purge, and an ejector air-purge arrangement. A scoop on the lower fuselage allowed ram air to enter the ammunition drum compartment. From there, the air flowed across the conveyor tunnel into the gun compartment and was expelled through an exhaust port in the gun fairing upper access door. The ram air was intended to purge the compartment of trapped gases, especially those accompanying spent cases being returned to the drum. Gun gases were drawn from the breech by an ejector using engine bleed-air and routed overboard through an exhaust port on the upper fuselage by the ejector air-purge system.

System operation was evaluated in ground tests using a section of the F-15 aircraft fuselage. The ram-air system was set for a range of airflows in combination with the ejector air system. Spark generators were placed at selected locations in the gun compartment to ignite the gun-gas and the pressure relief door was calibrated to open at 5 psig internal pressure.

Gun-gas ignition occurred with all gun bursts. On some tests, burst doors were blown open; in others, pressure rise was very slight (probably less than 1 psi). Gun-gas concentrations in some areas were significantly increased at lower purge airflows and were noticeably affected by different fairing/diffuser combinations.

Adequate protection was obtained throughout the operational flight envelope. Total vent area of 195 square inches was enough to safely relieve pressures generated by gun-gas ignition within the gun system compartments without the aid of the ram air and ejector air-purge systems.

Based on these test results, the system was redesigned to eliminate the ram-purge system and the ejector. The doors were replaced by louvers which are permanently open. The vent ratio in the final design is 3.47, which is considered adequate to maintain safe conditions in the compartment.

"GAU-8/A 30-MM Gun Flight Test Program Flight Test Engineering Report, FT 130REB02 Part II, 15 June 1974, Fairchild Republic Co., Reference 12.

"A-10A Airplane GAU-8/A Gun Qualification Tests, Parts 1 and 2," FT 160RFB08 21 October 1975, Fairchild Republic Co., Reference 13.

In the A-10, gun-gas was eliminated from the gun compartment by a ram-air compartment ventilation (scavenge) system and ejector-powered breech evacuation (purge) system. The scavenge system included a ram-air inlet on the bottom of the fuselage with a 40-square-inch area. This air was vented overboard through several louvered exits, totaling 130 square inches, to ensure proper distribution. The ventilation system operated at all times with no valves or other devices.

The purge system which evacuated the gun breech consisted of a shroud over the breech connected to a 4.5-inch-diameter duct routed through the compartment skin. An engine bleed-air powered ejector was powered throughout firing and for 30 seconds after termination of firing signal extracted gun-gas from the breech area.

A spring-loaded door, which was designed to open at a 1.5 psi differential between the internal and external pressures, was installed on the fuselage lower surface to provide gun compartment overpressure relief in the event of a gun-gas explosion in the compartment. During the flight-test program, the spring loaded-to-close door opened and closed as a function of airspeed and gun purge system operation. To alleviate these oscillations, the door was removed and the area allowed to remain open. During subsequent flights with the various external gun-gas deflectors, the door was reinstalled and locked closed with a breakaway structure designed to fail at 2 psi differential across the door. No activity was noted after this change.

Four gun-gas detectors were mounted in the nose section and gun compartment of the aircraft. The maximum gun-gas concentration recorded was 33 percent of lower flash limit following a 2.5-second burst; the next highest was 27 percent during a 3-second burst. The maximum recorded during bursts of

2 seconds or less was 20 percent, with the majority of measurements falling below 11 percent. One gun compartment sample was analyzed for carbon monoxide content and was determined to contain 706 parts per million (ppm).

During the flight-test program, the structure, flight instruments, subsystem, flight controls, and internal environment were not adversely affected by the gun system or gunfire with the purge system shut off. It was, therefore, recommended that the purge system be eliminated.

LIQUID-PROPELLANT AIRCRAFT CANNON

The Liquid-Propellant Gun (LPG) is a recently developed innovation which shows promising potential as an aircraft weapon. Its feasibility has been established, but practical utilization has not been accomplished to date.

Originally, it was intended to investigate the hazards associated with the LPG in future aircraft gun compartments, but as the investigation of the LPG progressed, it became apparent that practical utilization of this type of weapon might be many years in the future. In addition, the Navy, Air Force and several contractors are investigating the design, installation, and hazards associated with this type of weapon. The LPG installation and use would be drastically different than conventional solid-propellant gun installations.

Prior to mutual agreement between Rockwell and the Project Engineer to terminate the LPG effort on this program, Rocketdyne provided significant data and information on the LPG that they were studying. Excerpts from their report containing pertinent data and information is reported in the following paragraphs.

GUN GASES FROM LPG

In the overall context of gun-compartment gas hazard assessment it seems appropriate to look at new potential types of guns as well as other types of gun propellants. Both gun and propellant significantly affect the hazard level. Rocketdyne currently has a contract (F04611-76-C-0020) with the Air Force Rocket Propulsion Laboratory, Edwards AFB, Calif., for development of a liquid-propellant aircraft cannon. Some of the pertinent details of that program are presented in the following paragraphs.

Since thermochemical calculations had already been made to define the impetus levels of the various liquid-propellant compositions, these data were perused for applicability to the hazards assessment program. (See Figure 7.) Pertinent gas composition data were extracted from the thermochemical printouts. It was readily apparent that hydrogen peroxide/ethanol

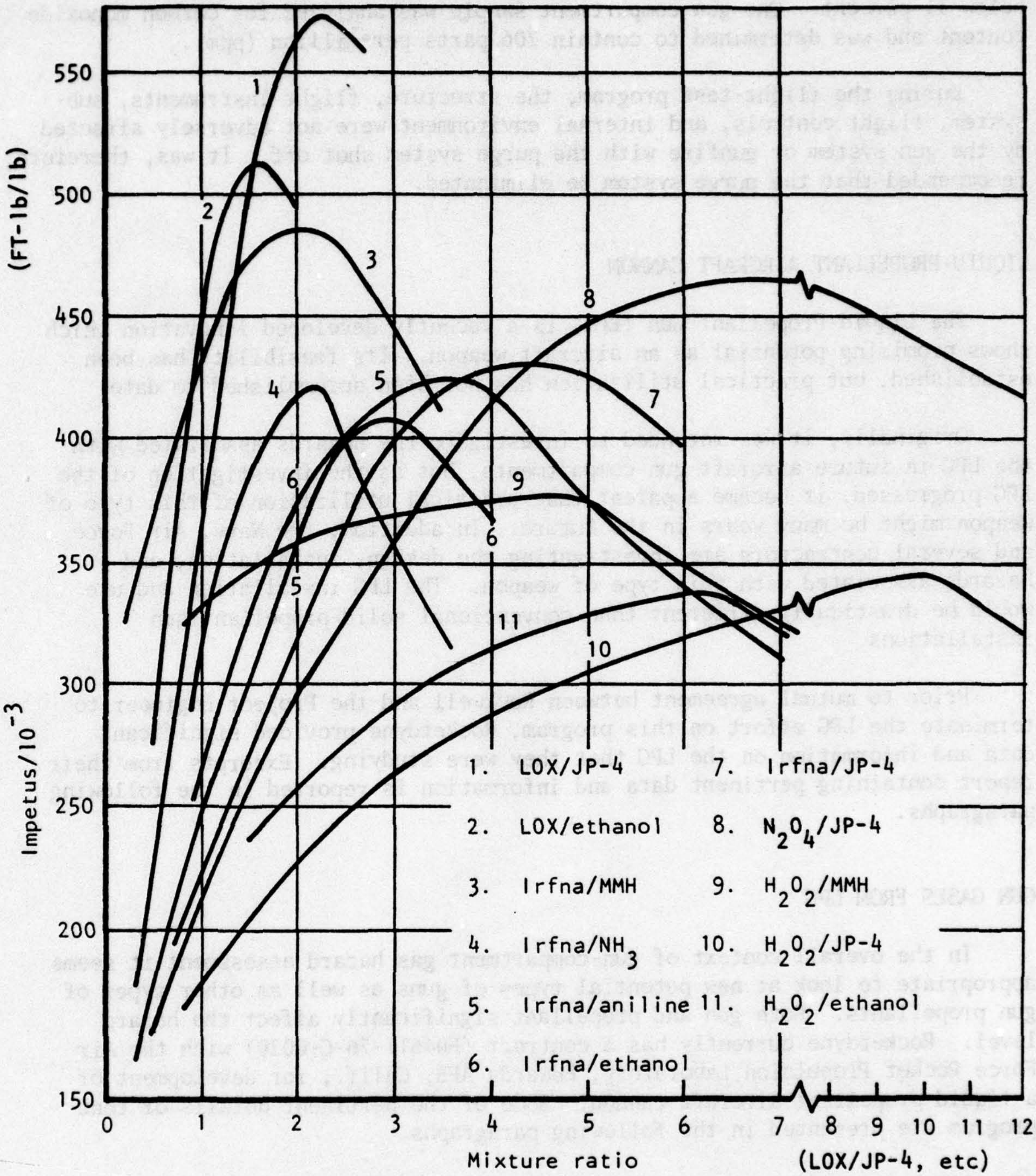


Figure 7. Propellant impetus for bipropellant liquid cannon.

would be an ideal propellant combination from the standpoint of gun-gas hazards since virtually all the gases evolved are noncombustibles. Unfortunately, however, other factors, i.e., impetus, will be the deciding factors for liquid gun-propellant selection. Since we do not know which propellant combination may prove successful, it is premature to speculate on the gun compartment hazards. In fact, the method of mounting a liquid-propellant aircraft cannon on the aircraft will be substantially different from current gun installations since the gun design incorporates a recoil-cancelling exhaust nozzle. A cursory look at the concentrations of the reaction products is of some academic interest however. This is presented in Table 1.

HAZARD METHODOLOGY DEVELOPMENT

For continuity in terminology and for better interfacing with similar studies, a rigorous definition of a hazard was sought. MIL-STD-882 provided a definition and an explanation of relative severity. Paragraphs 3.13 and 3.14 of MIL-STD-882 are repeated herein.

3.13 Hazard. Any real or potential condition that can cause injury or death to personnel, or damage to or loss of equipment or property.

3.14 Hazard level. A qualitative measure of hazards stated in relative terms. For purposes of this standard, the following hazard levels are defined and established: Conditions such that personnel error, environment,

TABLE 1. FLAMMABLE GAS IN REACTION PRODUCTS
COMPOSITION (VOLUME %) AT 14.7 PSIA

Propellants	H_2	CH_4	CO	C	Total	LEL
H_2O_2/Ethanol 6.3/1.0	0.17	0	0	0	0.17	
IRFNA/MMH 1.8/1.0	19.66	1.92	1.50	0	23.08	5.4
LOX/JP-4 1.64/1.0	34.17	2.70	25.72	0	62.59	11.1
Otto II	22.46	4.83	6.71	23.39	57.39	11

design characteristics, procedural deficiencies, or subsystem or component failure or malfunction:

(a) Category I - Negligible

....will not result in personnel injury or system damage.

(b) Category II - Marginal

....can be counteracted or controlled without injury to personnel or major system damage.

(c) Category III - Critical

....will cause personnel injury or major system damage, or will require immediate corrective action for personnel or system survival.

(d) Category IV - Catastrophic

....will cause death or severe injury to personnel, or system loss.

Using this nomenclature, a list was made of all the known gun compartment hazards. As shown in Figure 8, these are:

Personnel error
Switchology
Pneumatic malfunction
Hydraulic malfunction
Electrical malfunction
Structural failure
Sealant failure
Gun malfunction or failure
Ammunition feed malfunction
Ammunition malfunction
Explosion/fire
Flammable gas and liquids
Toxic fumes and liquids
Radiation (EMP/EMI)
Enemy fire
Ingestion

Examination of this list shows at once the interrelationship of cause, result, and hazard, since many of these terms fit all three categories. As stated in Paragraph 3.13, a hazard is a real or potential condition -- it is not necessary for it to happen for it to be a hazard. The mere fact that it exists requires appropriate action.

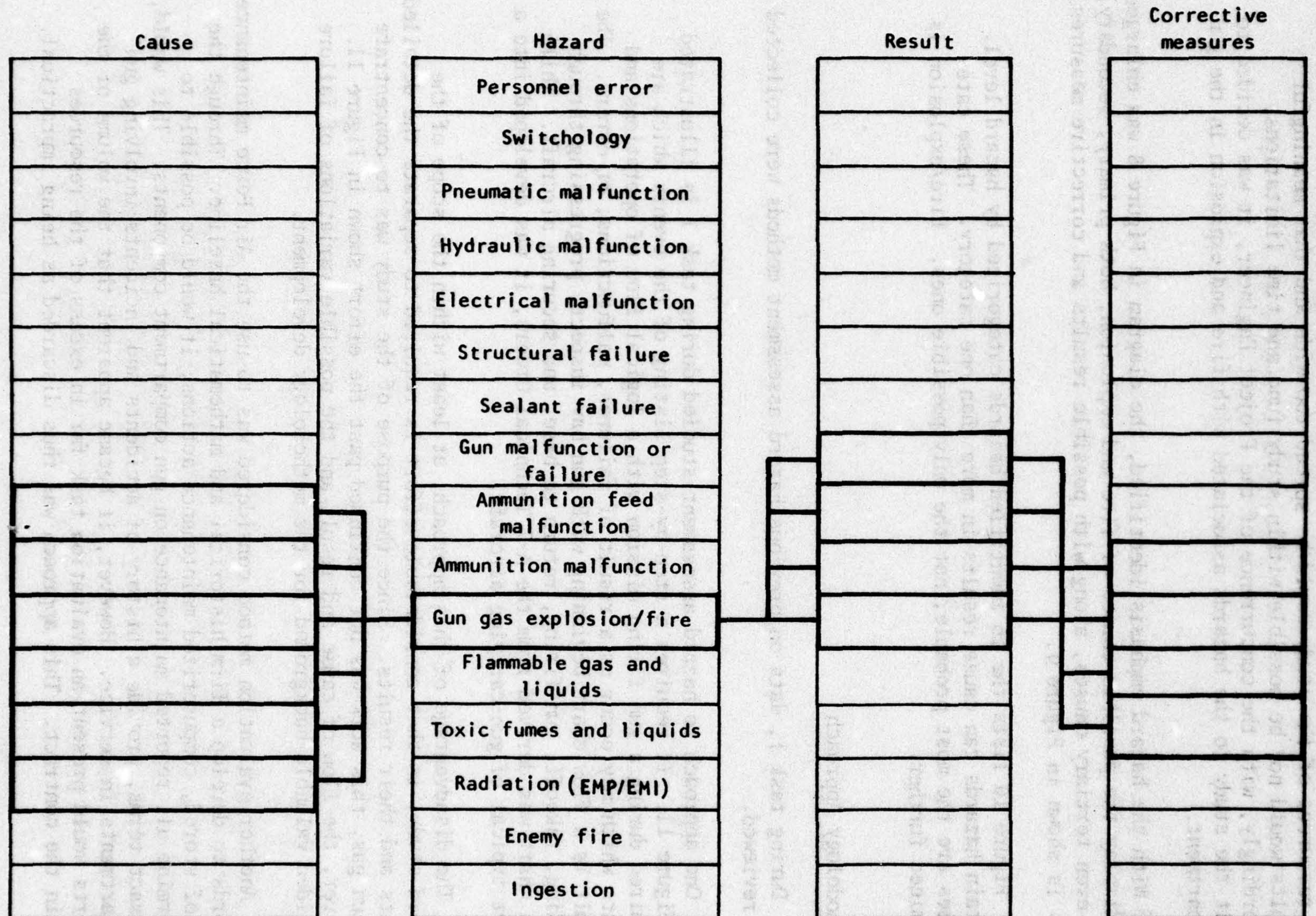


Figure 8. Hazard assessment methodology.

With this variety of hazards present, there was the real possibility that the resources of the study could be spread too wide and that meaningful results would not be possible within study fund and time limitations. Accordingly, with the concurrence of the Project Engineer, it was decided to limit the study to the hazards associated with fire and explosion in the gun compartment.

With the hazard emphasis identified, the diagram in Figure 8 was enlarged to display the possible causes of fire and explosion, both primary, secondary, and even tertiary causes, along with possible results and corrective measures. This is shown in Figure 9.

Figure 10 lists the 16 identified hazards categorized by hazard level. Certain hazards can cause results in more than one category. These categories are the most probable, not the only possible ones. Fire/explosion is examined further.

Methodology Approach

During task 1, data on previous hazard assessment methods were collected and reviewed.

One approach to hazard assessment studied during task 1 is illustrated in Figure 11. It requires a step-by-step listing of the events which are required during a gun firing mission with a logical flow of operations and events which may occur as a result of failures, malfunctions, or errors. The result is a flow chart beginning with gun bay inspect, progressing through loading, takeoff, gun firing, return to base, and securing aircraft. While this chart was derived from the A-7 Technical Orders, it was developed into a chart typical of gun-carrying aircraft.

The disadvantage of this approach, at least within the scope of the hazard study, is that considerable effort is required to separate the detailed events and their results. Since the purpose of the study was to concentrate on gun gas, this work was not continued past the effort shown in Figure 11. However, the flow of cause and result and the possible variations of failure provided valuable background for the methodology development.

Another evaluation method considered was to use the Air Force maintenance records to develop a firm historical and mathematical baseline. Through the use of stored, computerized maintenance actions, it would be possible to determine all reported maintenance on gun compartment components. This would, in exact terms, provide a history of accidents and incidents involving gun compartments in service. However, it became apparent that the volume of the reports would present an evaluation task far in excess of the resources within the contract. This approach was thus discarded as being impractical.

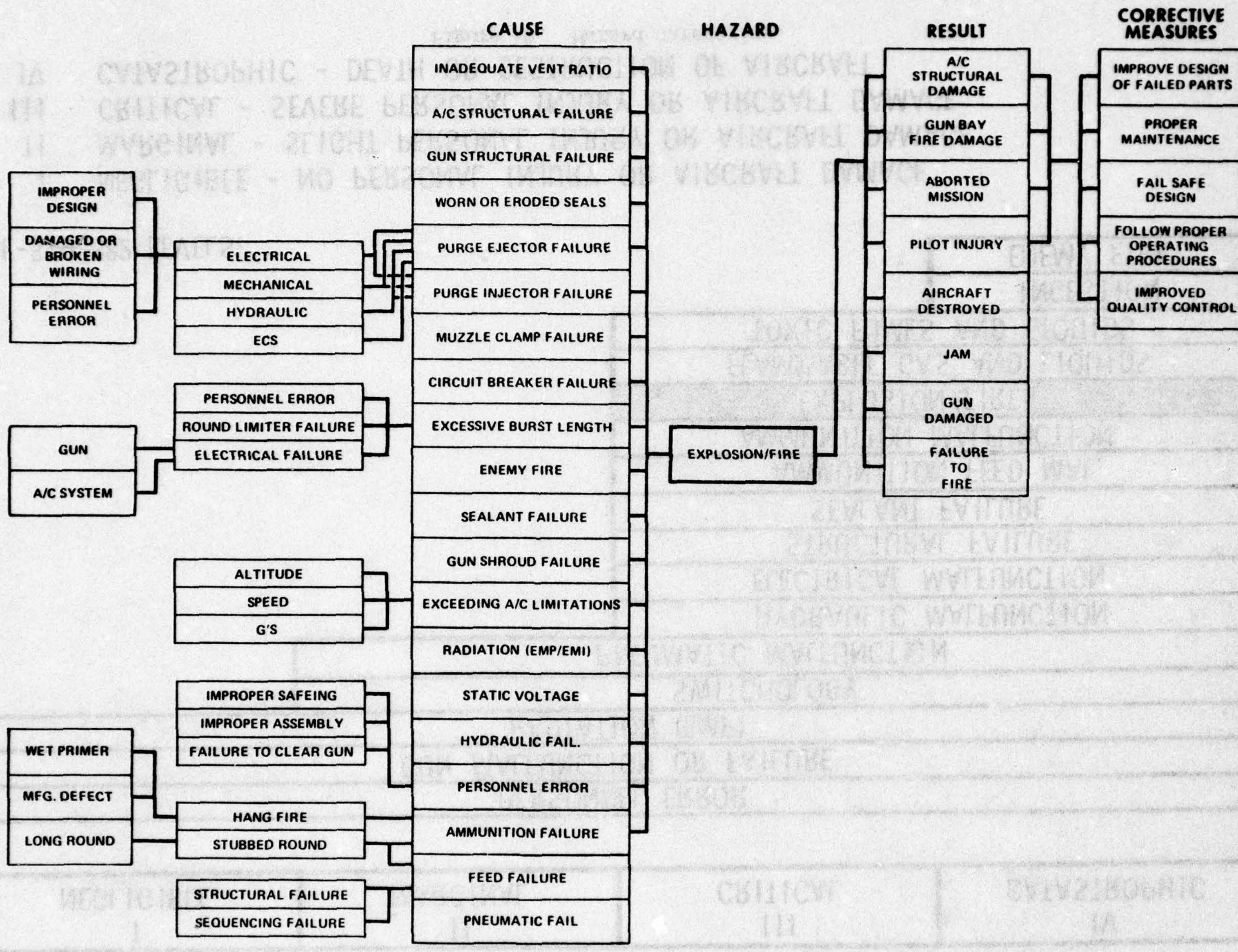
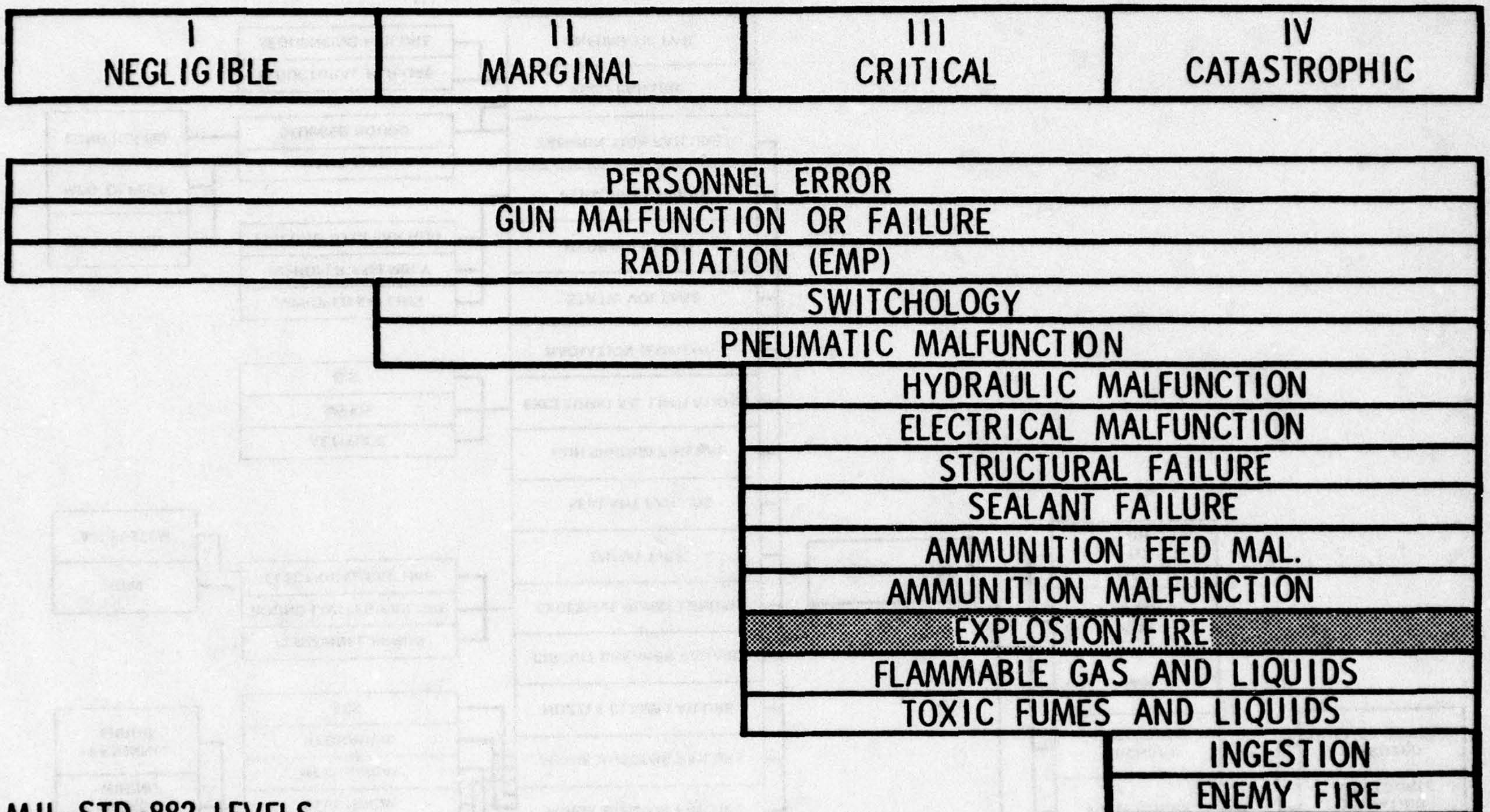


Figure 9. Gun gas, explosion/fire flow diagram.



MIL-STD-882 LEVELS:

I NEGLIGIBLE - NO PERSONAL INJURY OR AIRCRAFT DAMAGE
II MARGINAL - SLIGHT PERSONAL INJURY OR AIRCRAFT DAMAGE
III CRITICAL - SEVERE PERSONAL INJURY OR AIRCRAFT DAMAGE
IV CATASTROPHIC - DEATH OR DESTRUCTION OF AIRCRAFT

Figure 10. Hazard categories.

1. Inspect gun bay	2. Load ammunition	3. Secure gun bay	4. Start engines 5. Taxi 6. Take off 7. Cruise
Personnel error	Personnel error	Personnel error	Personnel error Switchology Electrical malfunct
Mechanical Improper assy Improper safing and locking Worn/broken parts Electrical Improper assy Worn/frayed wiring Component malfunct Switchology Hydraulic leakage Pneumatic leakage Failure to detect hot gun (cook-off, etc)	Improper sequence Improper assy Failure to detect hot gun Structural failure Feed malfunction Ammo failure/malf Feeder malfunction EMF	Failure to remove safing devices Failure to adjust limiting devices properly	
Results	**Results**		**Results**
Personal injury Falling articles Electrical shock Whipping lines/tubes Fluid loss Contamination of area Structural failure (breakage) Fire/explosion (cook-off) Inadvertent discharge Property damage	Personal injury Fluid loss Structural failure Fire/explosion Inadvertent discharge Blown circuit breaker		Inadvertent discharge Blown circuit breaker Personal injury Property damage

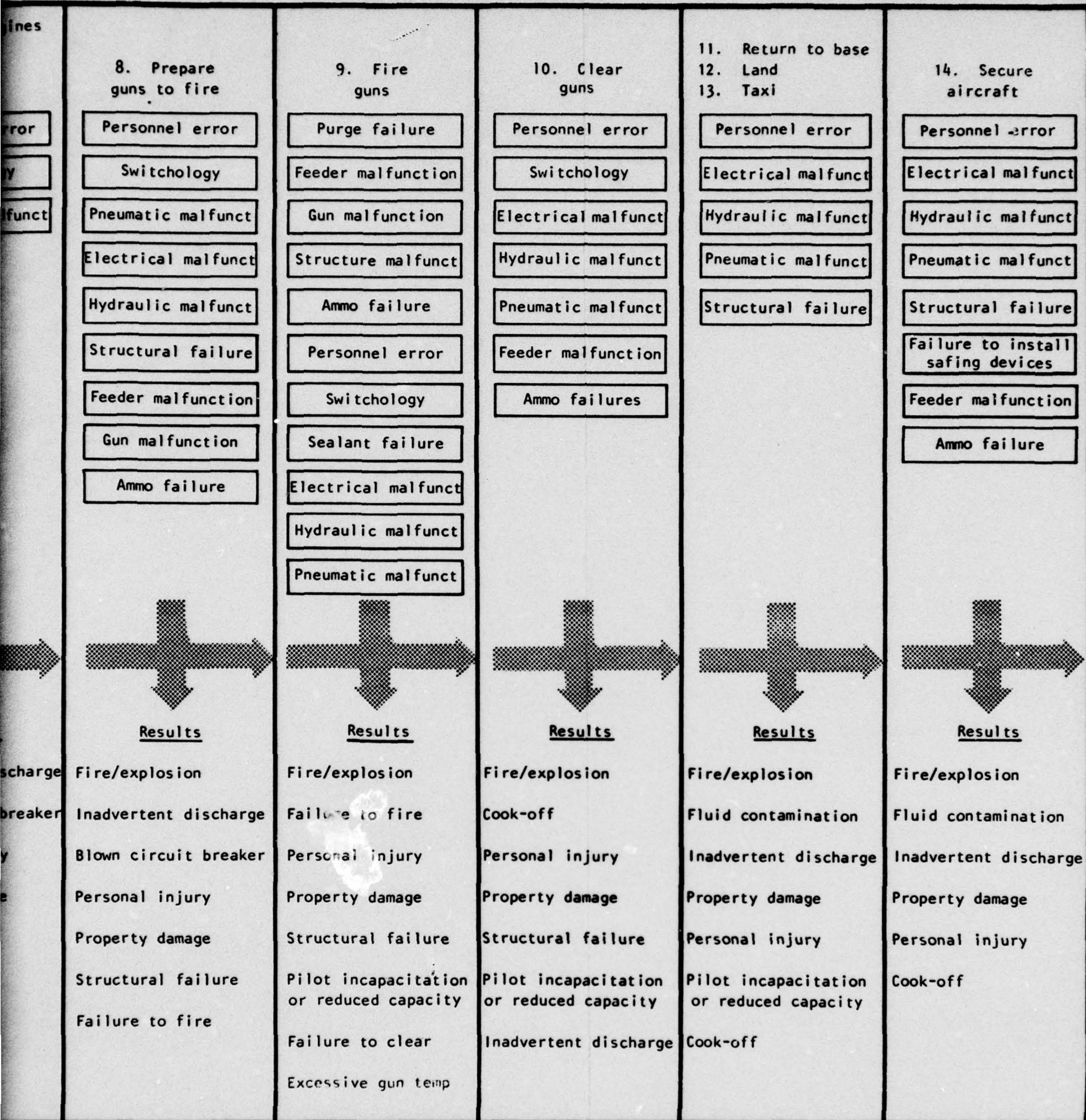


Figure 11. Gun bay hazards flow diagram.

The General Electric Company (Reference 14) had studied the hazards associated with the GAU-8 gun system in detail. The approach was to examine each system component, determine causes of possible failures, and assign values to the probability of occurrence and probability of damage or injury given an occurrence. This work was drawn upon extensively during the development of the methodology.

Review of hazard assessment methods included an evaluation of the magnitude and criticality of hazards with regard to personnel safety and mission success (Reference 15). The consequences of hazardous events may be minimal or may be catastrophic. Evaluation involves the likelihood of the hazardous event actually occurring. This may be reported in qualitative terms (certain, possible, unlikely, etc) or numerical terms.

Definition of the term "hazard", its application to the aircraft system and its relationship to the System Safety Program is detailed in MIL-STD-882. Within the Safety Program, timely identification of hazards and initiation of those actions necessary to prevent or control hazards is essential. Implementation of this requirement in the early design stages of the system with subsequent updates as development proceeds, followed by validation during the testing states, cannot be overemphasized. This involves integration and constant dialogue within the elements of the overall System Safety Plan.

The portion of MIL-STD-882 which defines and establishes the relative importance of hazards was reproduced earlier in this Section.

Application of the specified hazard criteria to this study was clarified by the large data base assembled during task 1. The identification and description of every recorded gun compartment-related accident/incident which was obtainable, made the type of approach described in MIL-STD-882 feasible. Stated simply, a solid data base is required to provide a usable basis of judgment. The accident/incident data formed a solid and unique basis for hazard methodology development.

The approach decided upon required an examination and categorization of the individual cases in a matrix of cause and result. These were listed and relative numerical values assigned based on the frequency of occurrence. The numerical sum of these occurrences formed a baseline. To test the methodology, it was then applied to two modern aircraft, the A-10 and the F-15, and the numerical values that resulted were compared to the baseline. As expected, both aircraft showed a lower thus better hazard index, validating, within the limitations of the procedure, the assumption that these recent designs had considered the experience gained from older aircraft and had investigated design and procedure improvements which will be effective in providing a safer gun compartment during future operations.

Methodology Development Result

Introduction

A comprehensive and meaningful evaluation of the gun compartment hazards requires a detailed systematic methodology whereby subsequent evaluation can be readily, uniformly, and intelligently compared. The techniques developed utilize elements of Failure Mode and Effects Analysis (FMEA) in combination with engineering logic and known typical gun compartment designs, combined by use of a mathematical weighting scheme.

The methodology developed and presented herein addresses only fires and explosions, the most serious of the 16 identified gun.compartment hazards. The other hazards are not within the scope of this effort, and therefore no further investigation, other than identification, has been attempted under this contract.

For the fire/explosion hazard, general causes identified as principal contributors to this hazard were assembled into 11 separate causes. Each general cause was categorized into seven classifications (as discussed later) to form the basis of the methodology. All known possible events (failures) were covered, and a baseline possibility of occurrence for that event established, thus providing a mathematical basis of comparison.

Definition and Ground Rules

The cause, hazard, and result interplay previously discussed made it necessary to establish definitions and ground rules. The following definitions were developed for this study.

1. Cause - An activity, event, or occurrence which creates a predefined hazard possibly leading to a predefined result.

2. Hazard - Consistent with MIL-STD-882 (3.13). The existence of any real or potential condition in or related to the aircraft gun compartment created by a predefined cause that imposes a high degree of risk of personal injury or death to the aircrew, or a high degree of risk of damage or destruction to essential aircraft parts, components, subsystems, or systems.

3. Result - An undesirable predefined activity, event, or occurrence that happened as a direct or indirect consequence of a predefined cause.

While all of the causes listed have the inherent capability, and in most cases the distinct probability, of causing a fire and/or explosion in the gun bay, a malfunction may not have that result. For example, gun structural failure often occurs without subsequent fire. Within the causes shown, other results are listed and evaluated, based on the assembled experience data as well as judgment.

To facilitate the display, and to simplify the understanding of the methodology, each general cause is displayed individually, with its generic flow diagram describing the interrelationship of the seven characteristics. Each general cause is displayed in the format shown in Figure 12. The appropriate definitions required to interpret the results are also contained in Figure 12. The figure also shows the summary sheet which is an integral part of the methodology, and the mathematical method of combining the possibility of occurrence (F_O) with the possibility of damage given an occurrence (F_{DO}) to arrive at the severity factor (S_F).

Starting with the cause, proceeding in turn to the operating condition, failure mode, and specific cause, it is possible to estimate F_O and F_{DO}. The product of the two is then S_F. Since some general causes may have multiple branches, the sum of the severity factors is defined as the severity index (S_I). The severity index for each general cause is then summed to determine the hazard index (H_I) for the entire gun system under consideration. The lower the H_I, the lower the fire/explosion hazard as compared to the baseline.

Any gun system can be evaluated using this methodology by assigning the appropriate possibility factor based on good engineering judgment or test data. However, care must be exercised to insure that additional causes and/or results cannot occur in the design under consideration. If there are additional causes and/or results within a predefined general cause, an additional branch can simply be added. If a new general cause is discovered, an entire new page is required.

The seven categories depicted in Figure 12 are defined as follows:

1. Component - The component or system that is primarily affected by the occurrence of the general cause (heavy border box).

2. Function - The task that the component or system is designed to perform when working properly.

3. Operative Condition - The general state that the component or system is in when it is not working as intended.

4. Failure Mode - The general type of failure that created the operative condition.

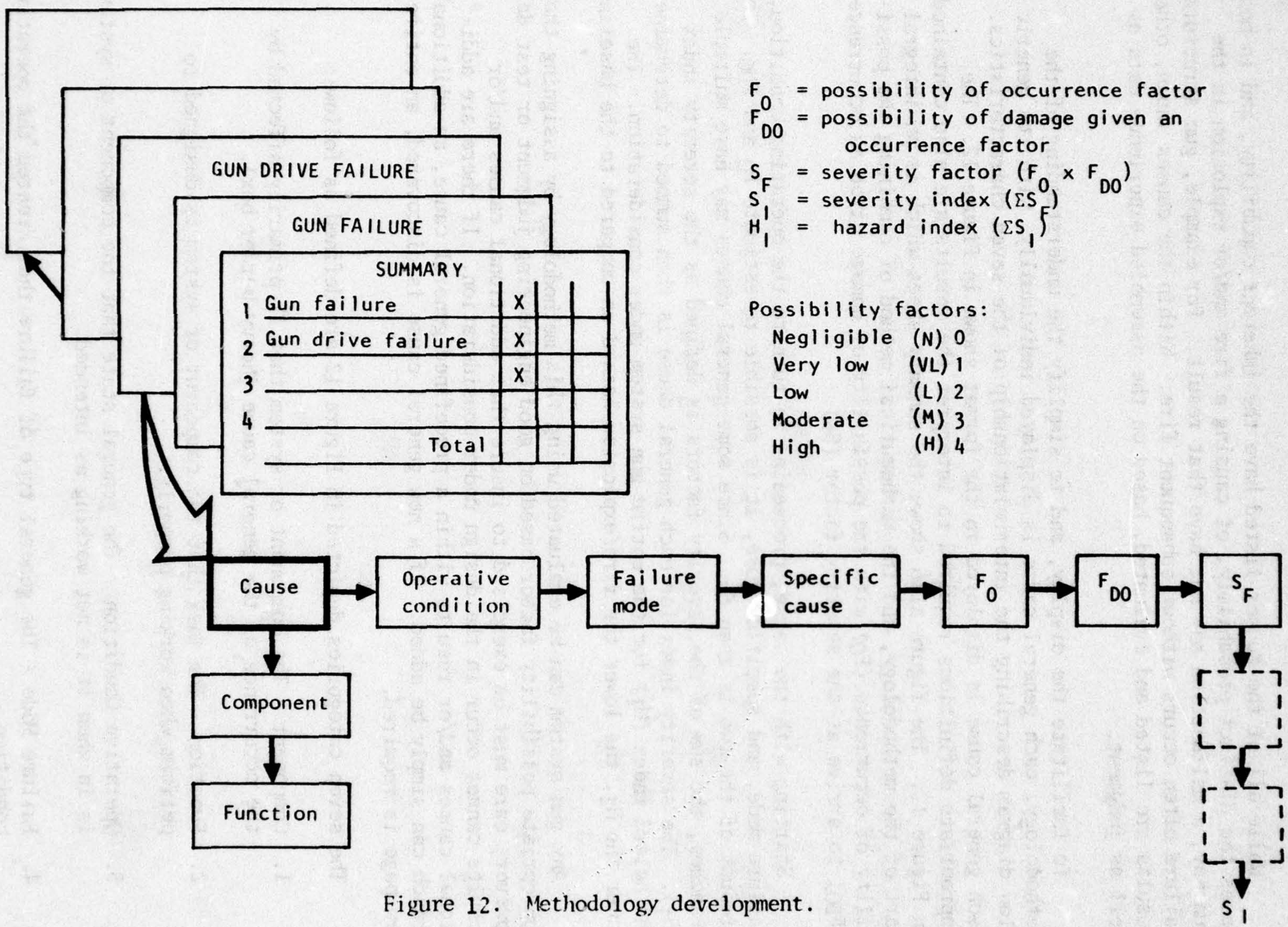


Figure 12. Methodology development.

5. Specific Cause - The specific reason the failure occurred.

6. The Possibility of Occurrence Factor (F_O) - The likelihood that the particular specific cause will occur. These factors are relative to the other causes, not the absolute probability of the event occurring.

7. Possibility of Damage Given an Occurrence Factor (F_{DO}) - The relative classification of the type and extent of damage that is likely to occur if the specific cause occurs. These factors are relative to the other damage factors, and are not absolute probability terms.

Generic Gun Compartment (Baseline)

For the fire/explosion hazard, the following 11 general causes have been identified through accident/incident reports, test programs, and engineering judgment. An effort was made to exhaust all possible methods of failure, but there is always a slight possibility that a new design can fail in a way not generically predicted. Thus, each new design must be carefully examined to determine that all possible failure modes have been accounted for and appear on the methodology flow charts.

Any general cause can be modified by adding additional branches, or entirely new general causes can be developed. Once developed and the modified charts prepared, the evaluation proceeds the same.

For continuity and ease of cross-reference, the causes are arranged in the same order as the accident/incidence frequency matrix (Figure 6), that is, gun, drive, feed, etc.

1. Gun Failure (Figure 13)

   a. Function and Component - The function of the gun is to fire the ammunition.

   b. Operative Condition - There are eight operative conditions:

      (1) Seal failure

      (2) Structural failure

      (3) Jam

      (4) Double feed

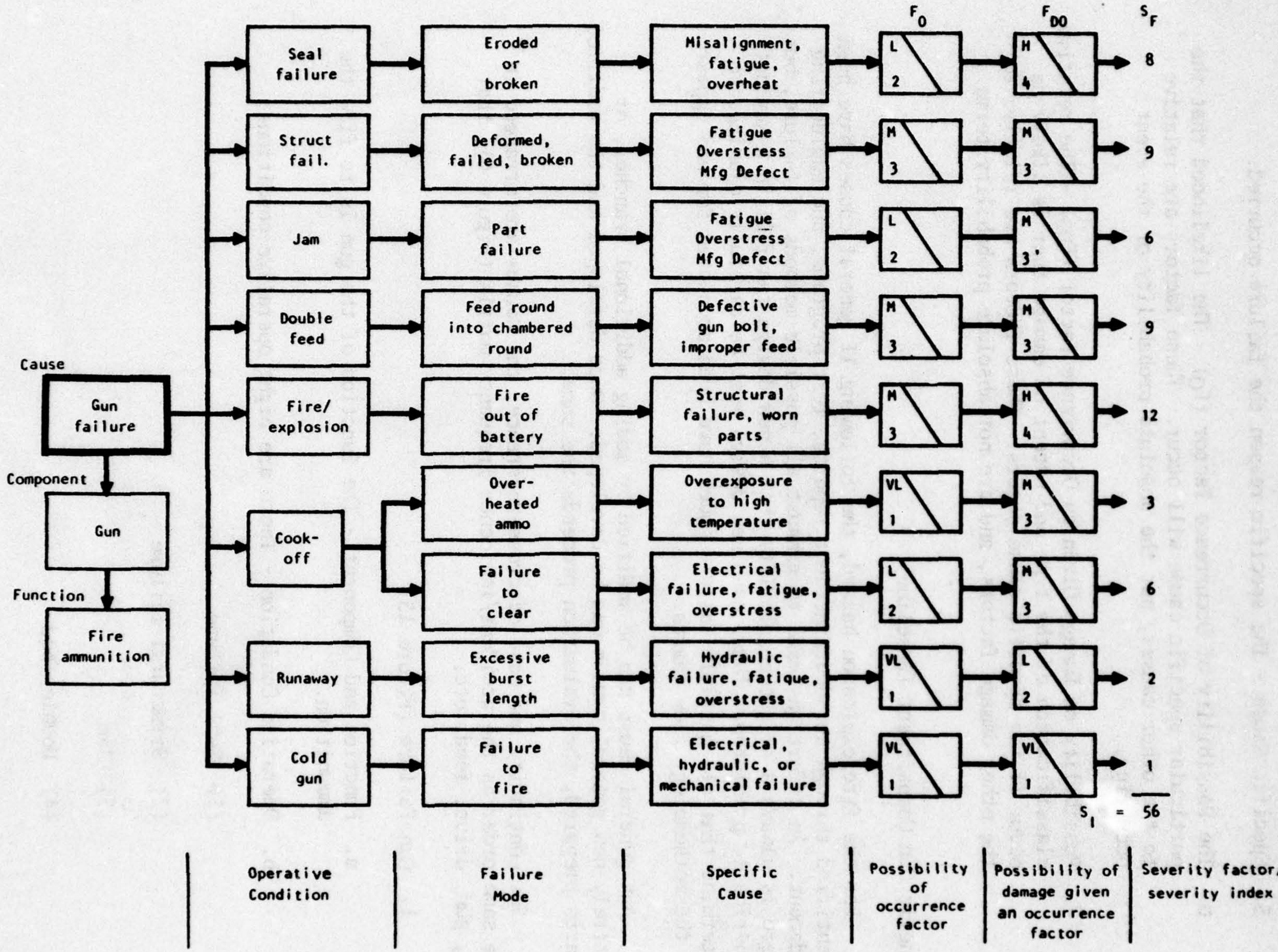


Figure 13. Gun failure.

(5) Fire/explosion

(6) Cookoff

(7) Runaway

(8) Cold gun (failure to fire)

c. Failure Mode - These are listed for each condition. For example, seal failure may be caused by eroded or broken parts.

d. Specific Cause - This is the actual estimated cause based on operating experience and an engineering evaluation of the operating characteristics of the gun. Seal failure may be caused by misalignment, fatigue, or overheating.

e. Possibility of occurrence F_O - The estimated possibility of this occurring is low, consequently a numberical value of two is assigned.

f. Possibility of Damage Given an F_{DO} - If seal failure should occur, the possibility that damage to the gun and gun compartment will occur is estimated to be high. A value of four is thus assigned.

g. Severity Factor (S_F) - Multiplying F_O x F_{DO}, the resultant eight gives the severity factor for seal failure as a cause of gun failure. This procedure is followed for each of the other seven operating conditions and S_F assigned to each. Finally, the S_I is determined by summing the individual S_I values. The S_I represents the estimated baseline or generic S_I. As shown for gun failure, the S_I is 56.

2. Gun Drive Failure (Figure 14)

a. Function and Component - The function of the gun drive is to rotate the gun for gun firing. It is applicable to externally powered guns such as Gatling types.

b. Operative Condition - There are three conditions, which are:

(1) Failure to operate

(2) Failure to stop (runaway)

(3) Creep

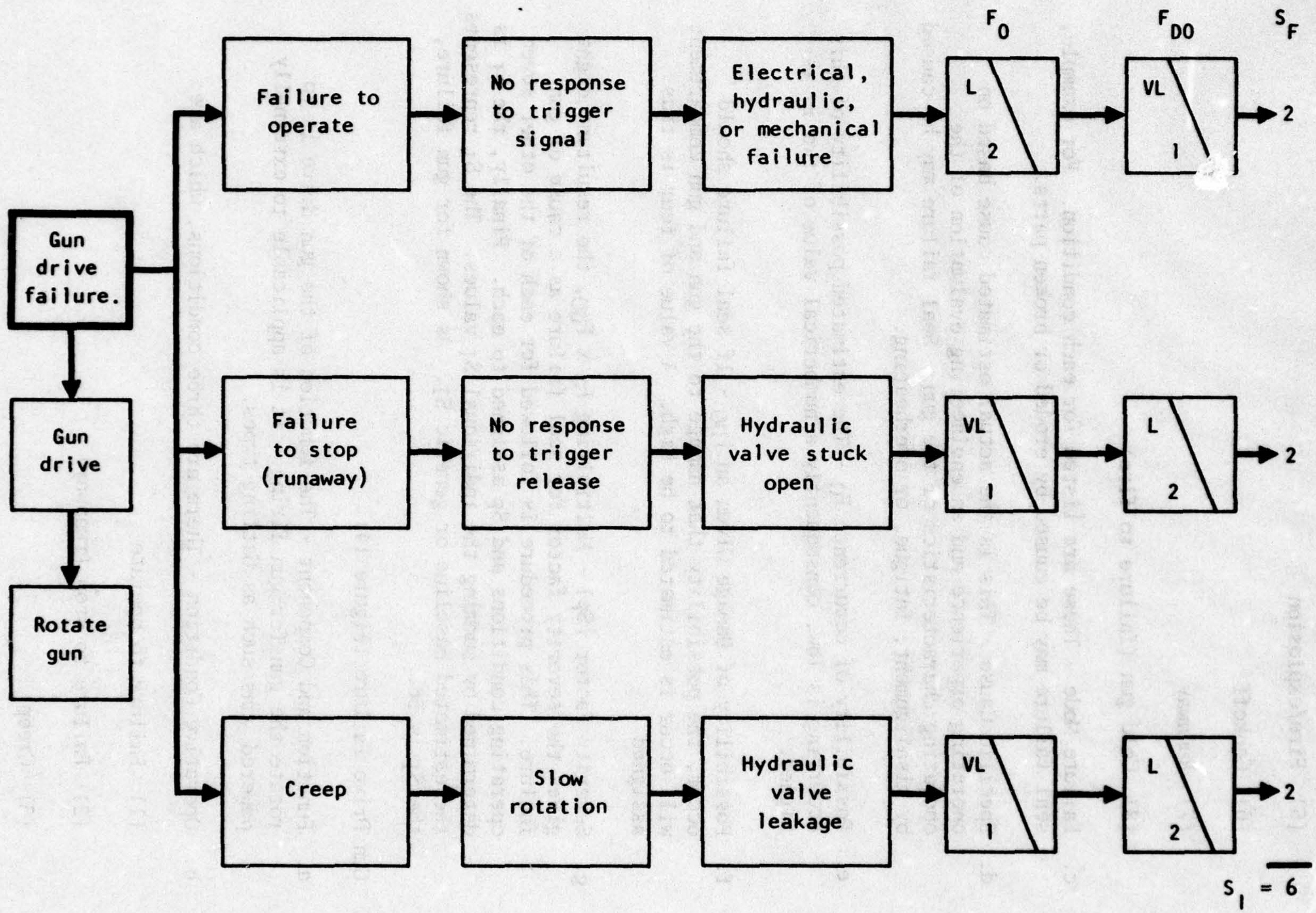


Figure 14. Gun drive failure.

c. Failure Mode - Each mode is shown.

d. Specific Cause - Each cause is shown.

e. Severity Index - The S_I is six.

3. Feed Failure (Figure 15)

a. Function and Component - The function of the feed system is to store the ammunition and feed it to the gun. For continuous systems, it also returns unexpended rounds and empty cases to storage.

b. Operative Condition - There are four conditions, which are:

(1) Jam

(2) Improper round hand-off

(3) Latch failure

(4) Structural failure

c. Failure Mode - Each mode is shown.

d. Specific Cause - Each cause is shown.

e. Severity Index - The S_I is 42.

4. Purge Failure (Figure 16)

a. Function and Component - The function of the purge system is to purge the gun compartment of gun-gas by introducing sufficient air to keep the mixture within acceptable limits.

b. Operative Condition - The single condition is inadequate airflow.

c. Failure Mode - The modes are listed. Failure to operate could mean failure of the purge inlet doors due to linkage breakage, inadequate power, or could mean failure of the purge ejector to operate so that gas scavenging is impaired. Inadequate vent ratio is a basic design problem that may prevent adequate purging no matter how much purge air is introduced into the compartment. Environmental Control System (ECS) failure is applicable when the aircraft ECS is required to actuate the purge system, either by injector, ejector, or both, and the ECS system fails. Gun shroud failure applies to those installations in which a shroud is placed over or around the gun breech to

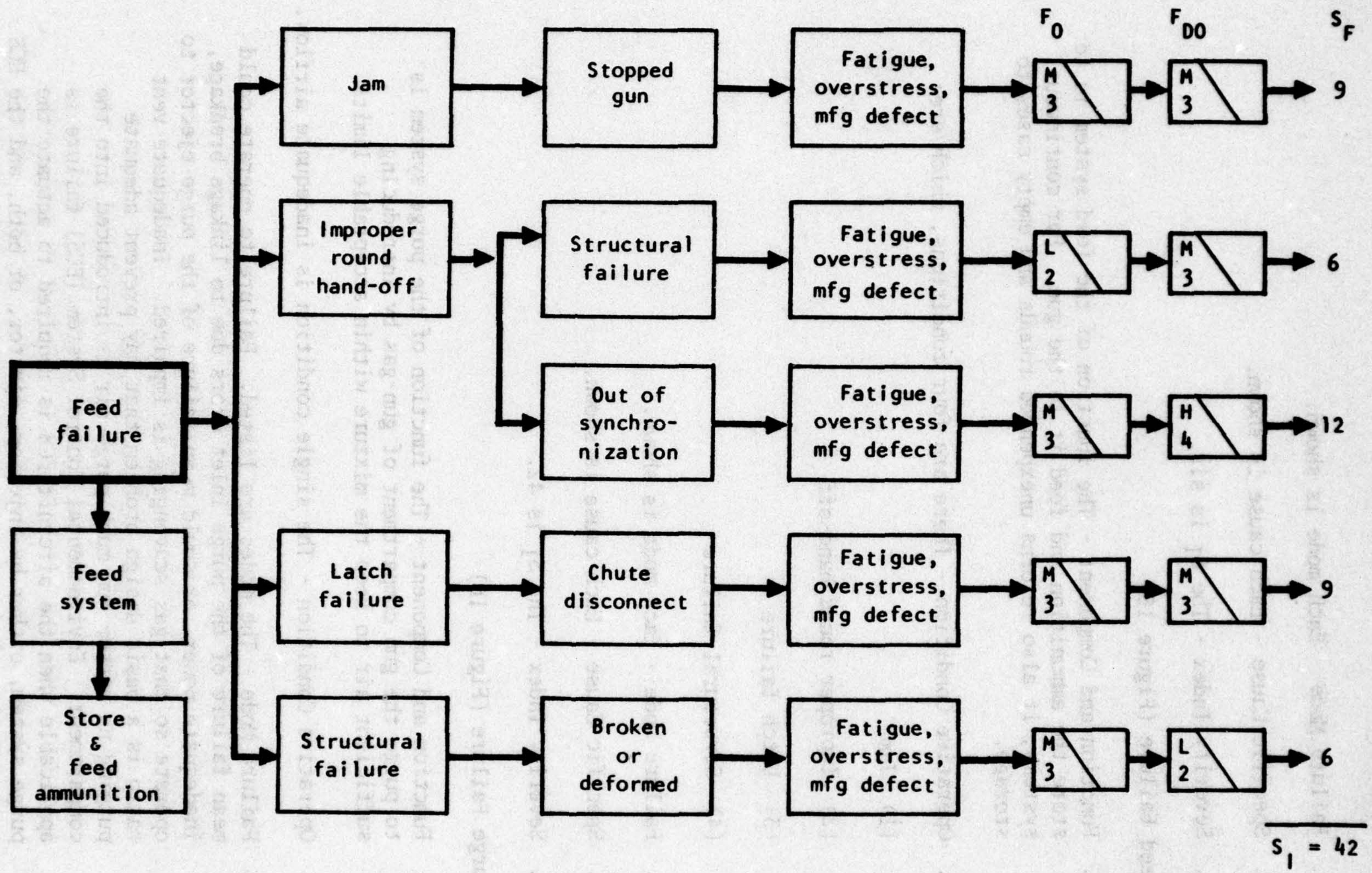


Figure 15. Feed failure.

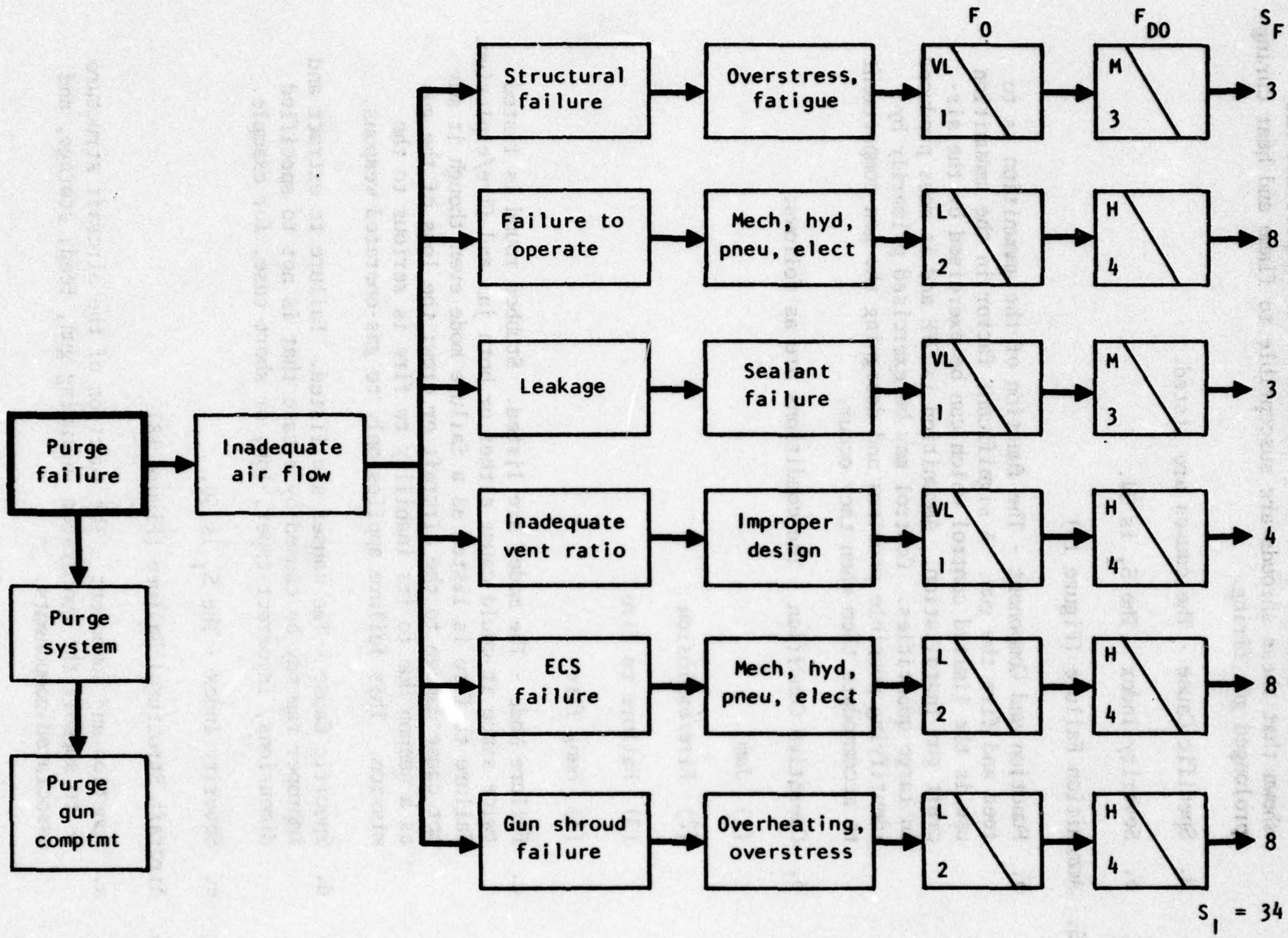


Figure 16. Purge failure.

collect the gas and vent it to a safe area. Experience has shown that these shrouds are susceptible to flame and heat during prolonged gun firing.

d. Specific Cause - The causes are listed.

e. Severity Index - The S_I is 34.

5. Ammunition Failure (Figure 17)

a. Function and Component - The function of the ammunition is to feed and fire the gun. A significant factor in the ammunition use is the limited control which can be exercised by the aircraft gun installation. Ammunition is GFE and is mass produced in large quantities. Control may be exercised primarily by identifying possible problems and designing the gun compartment to accommodate them when they occur.

b. Operative Condition - The conditions are as follows:

(1) Jam

(2) Fire/explosion

(3) Failure to fire

(4) Hang fire

c. Failure Mode - The modes are listed. Stubbed round is listed twice since it could cause either or both jam and fire/explosion. Failure to fire is listed as a failure mode even though it may not cause damage to the aircraft or crew; the loss of the gun as a weapon due to its inability to fire is serious to the mission. This failure applies only to gas-operated weapons.

d. Specific Cause - The causes are listed. Failure to extract and improper ram may be caused by a case that is not to specified dimensions, incorrect taper, long or short case, for example.

e. Severity Index - The S_I is 50.

6. Aircraft Structural Failure (Figure 18).

a. Function and Component - The function of the aircraft structure is to support the gun system including gun, feed, storage, and associated components.

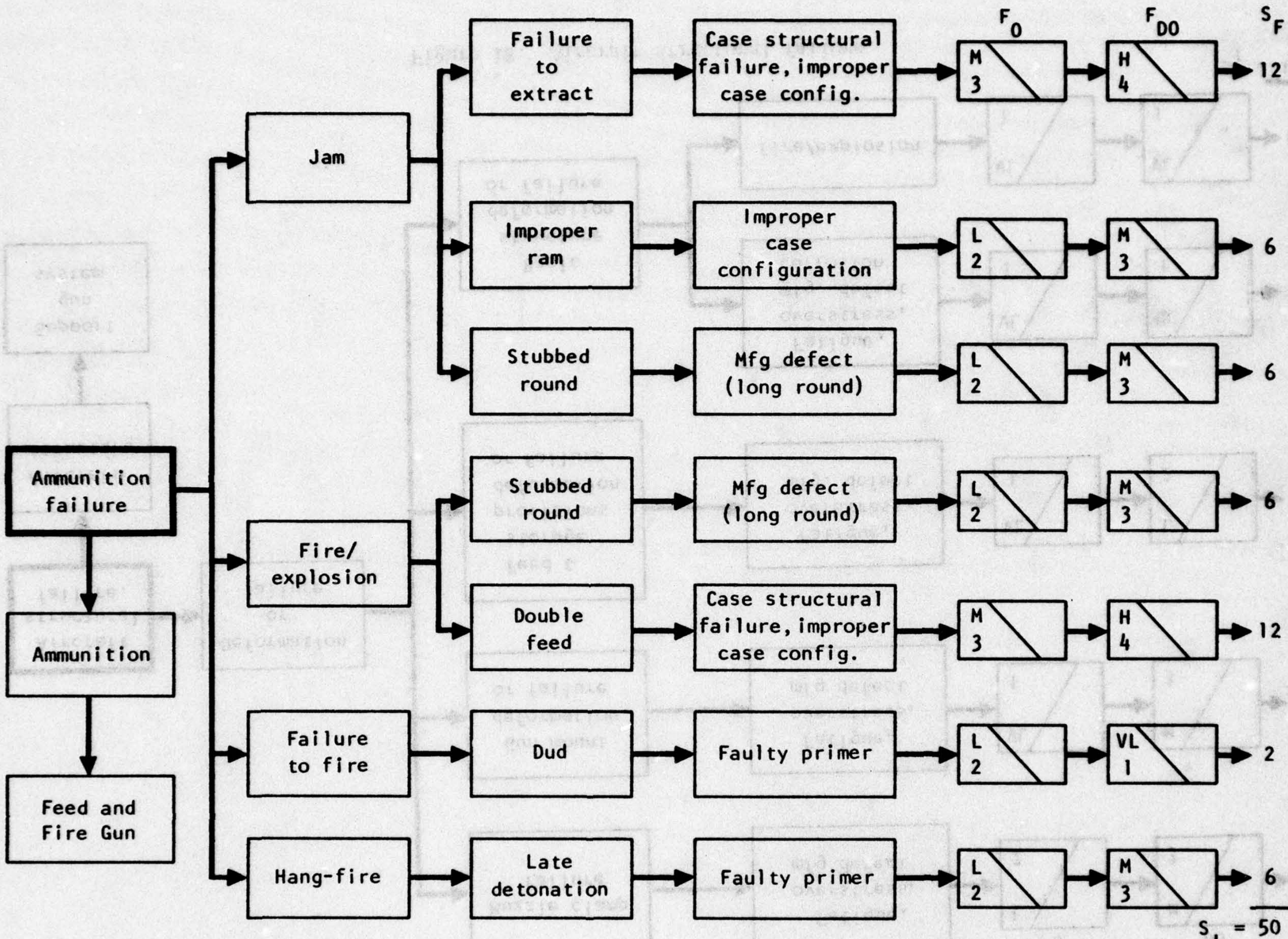


Figure 17. Ammunition failure.

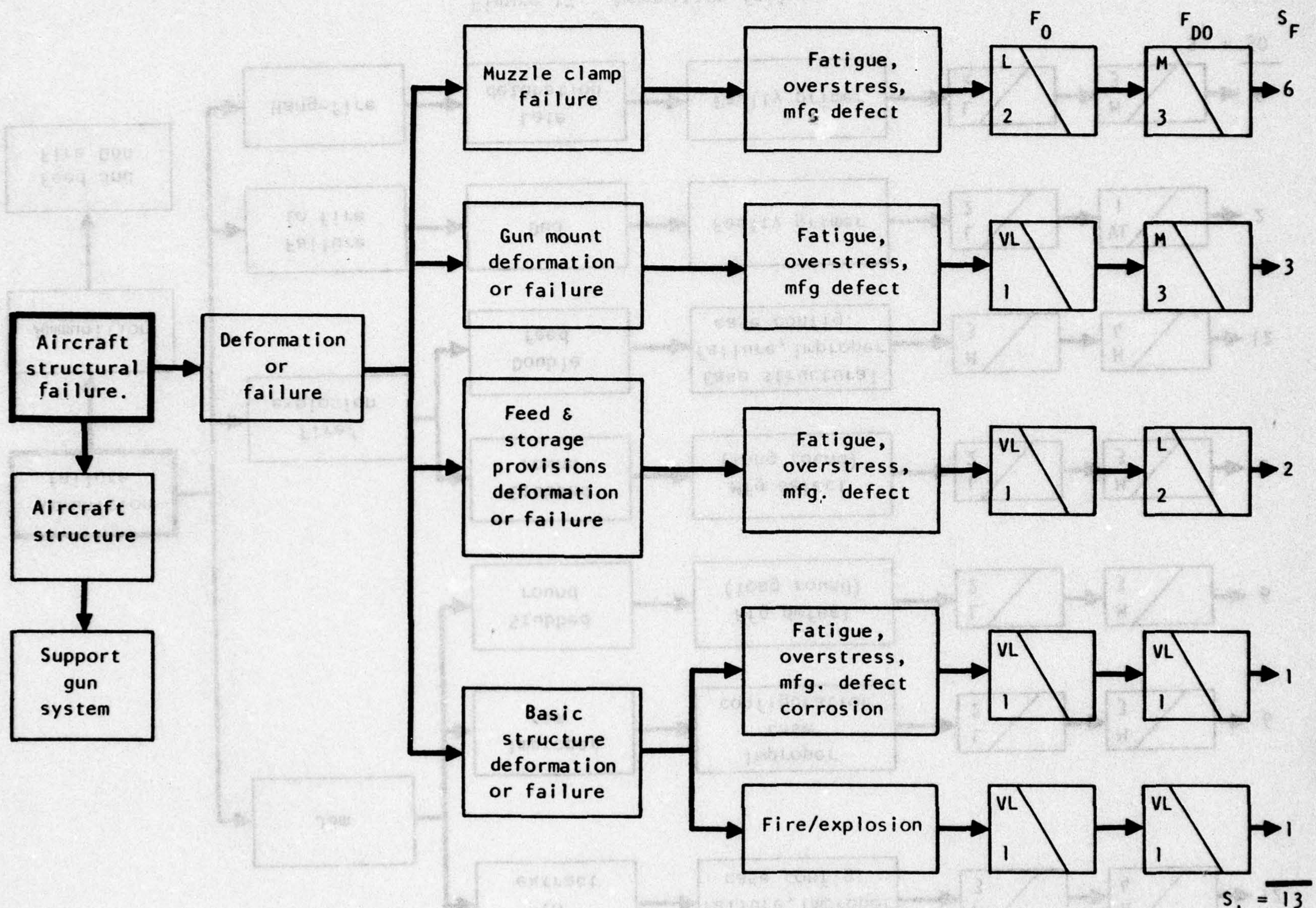


Figure 18. Aircraft structural failure.

b. Operative Condition - The single condition is deformation or failure.

c. Failure Mode - Four areas affecting gun compartment hazards are identified; muzzle clamp failure, gun mount deformation or failure, feed and storage provisions (structural support and attachments) deformation or failure, and basic bay structure deformation or failure.

d. Specific Cause - The causes are listed.

e. Severity Index - The S_1 is 13.

7. Aircraft Systems Failure (Figure 19)

a. Function and Component - The function of the aircraft systems, including hydraulic, electrical, and pneumatic systems, is to supply power and control to operate the gun system.

b. Operative Condition - The single condition is failure or malfunction.

c. Failure Mode - The modes are listed for each of the systems.

d. Specific Cause - The causes are the same for all modes (fatigue, overstress, and manufacturing error).

e. Severity Index - The S_1 is 16.

8. Personnel Error (Figure 20)

a. Function and Component - The function of personnel who are included in this category is to operate and maintain the aircraft gun compartment, including the systems and all their components. Many of the other failures listed herein may be caused by personnel error, however, significant conditions caused by personnel have been grouped together for simplicity.

b. Operative Condition - The conditions are listed. Hot-gun is a condition in which a live round is chambered in the breech when the gun should be clear. Improper firing refers to actual gun firing when it should not be firing.

c. Failure Mode - The modes are listed. Improper operation refers to system operation such as to create an unsafe condition, excessive burst firing, for example. Exceeding operational limitations describes a situation in which the aircraft is operated under conditions for which it was not designed. One

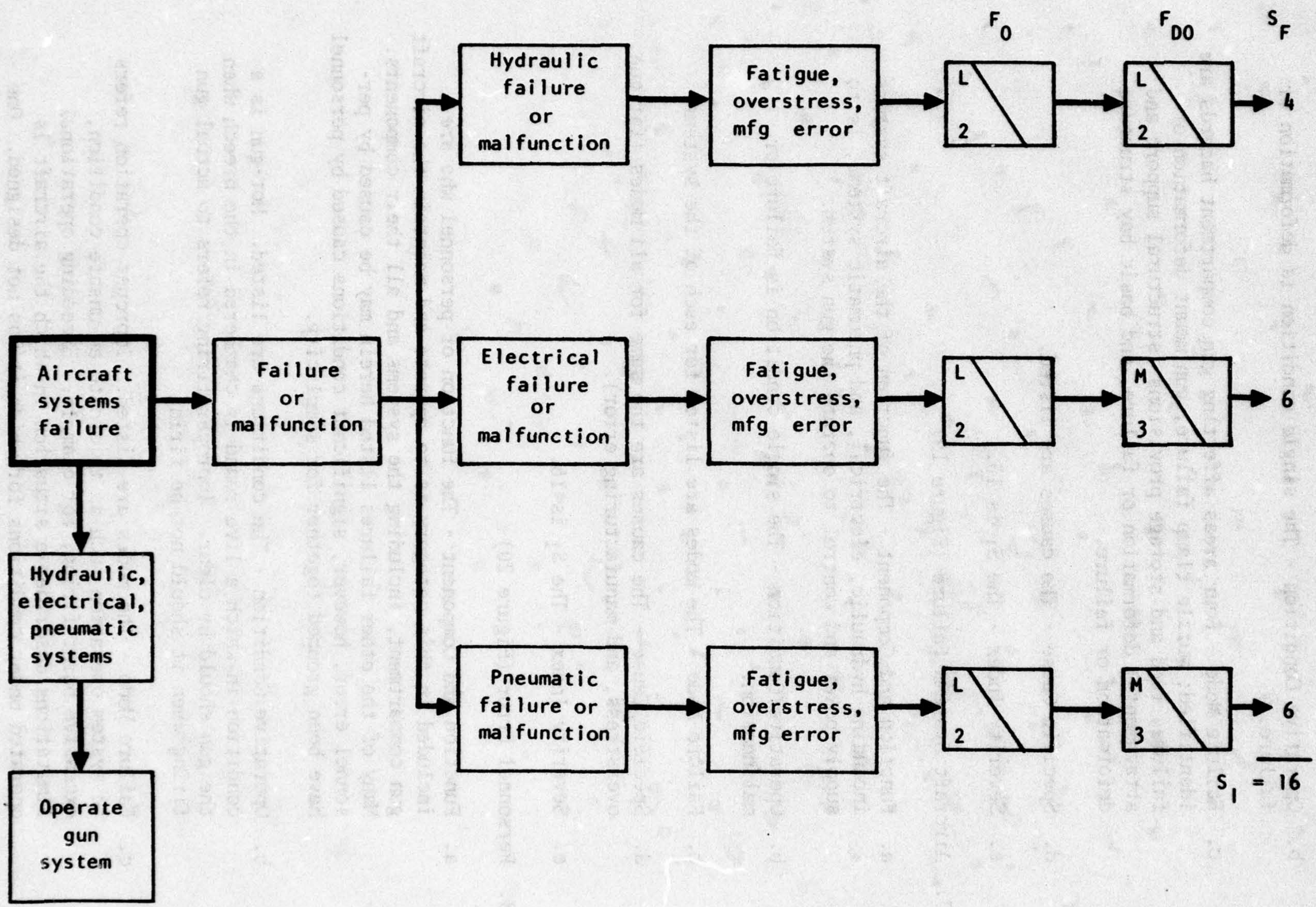


Figure 19. Aircraft systems failure.

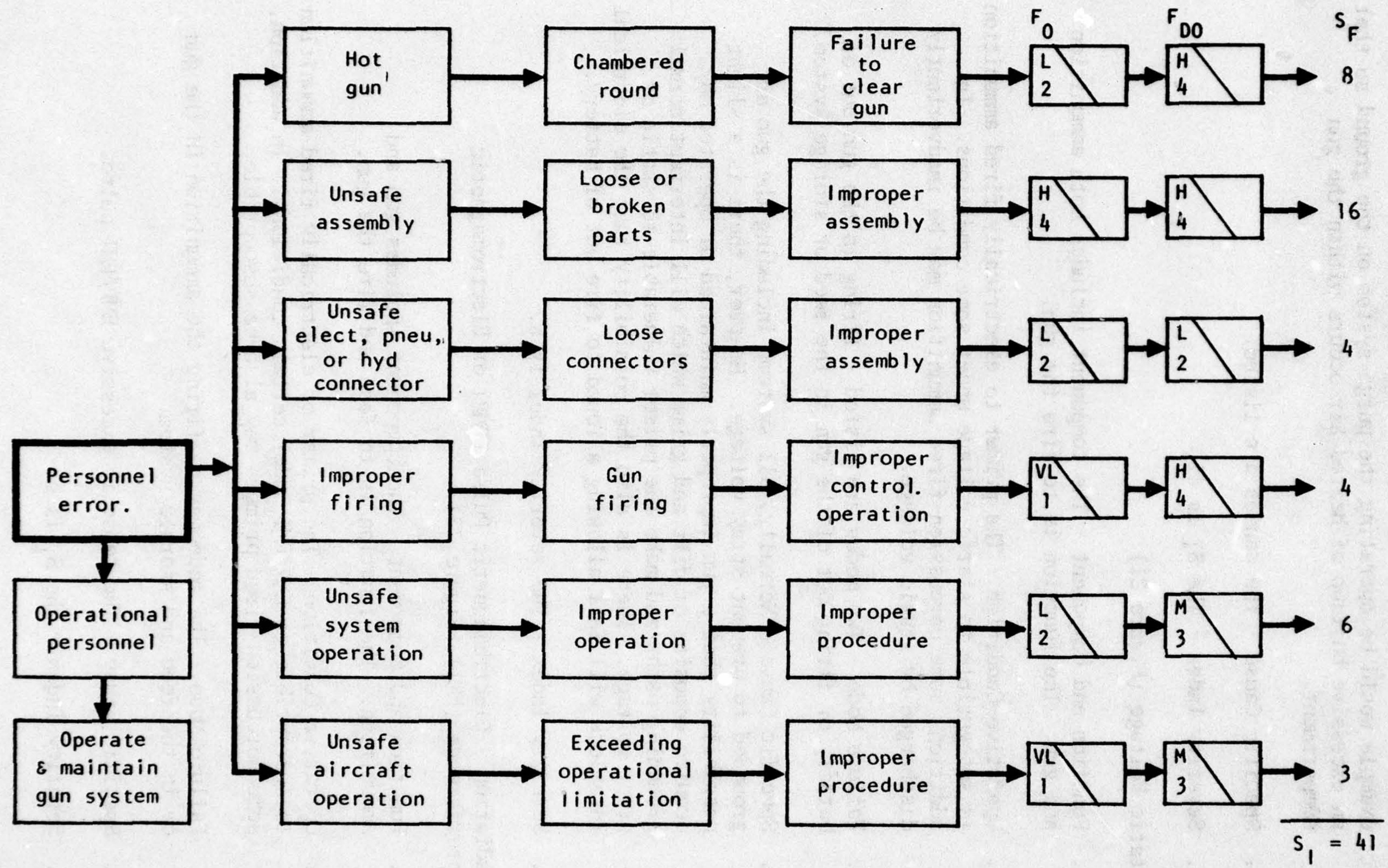


Figure 20. Personnel error.

example would be operating the purge system on the ground so that an excessive buildup of heated air occurs within the gun compartment.

d. Specific Cause - The causes are listed.

e. Severity Index - The S_I is 41.

9. Static Voltage (Figure 21)

a. Function and Component - The component includes both ammunition and gun. The function is to fire the gun.

b. Operative Condition - The primer to electrically fired ammunition is susceptible to static voltage under some conditions. In addition, some percussion-fired ammunition may be inadvertently discharged by static voltage.

c. Failure Mode - Two modes are listed - firing in the gun out of battery or firing out of the gun in the feed or storage system.

d. Specific Cause - Normally, all systems including the gun are grounded to prevent stray voltage. However, there is a slight possibility that a gun improperly maintained or operated may acquire deposits of dirt and grime which will interrupt normal grounding paths and make the primer vulnerable to static or stray voltage. There is also the possibility that the electrical interlock will fail allowing a round to fire out of battery.

e. Severity Index - The severity index is 6.

10. Radiation - Electromagnetic Pulse (EMP) or Electromagnetic Interference (EMI) (Figure 22)

a. Function and Component - The component includes gun and ammunition. The function is to feed and fire the gun.

b. Operative Condition - The primer of electrically fired ammunition is susceptible to EMP/EMI under certain conditions. In addition, some percussion-fired primers may also be susceptible.

c. Failure Mode - The mode may be firing the ammunition in the gun or in the feed and storage system.

d. Specific Cause - The cause is excessive EMP/EMI pulse.

e. Severity Index - The S_I is 6.

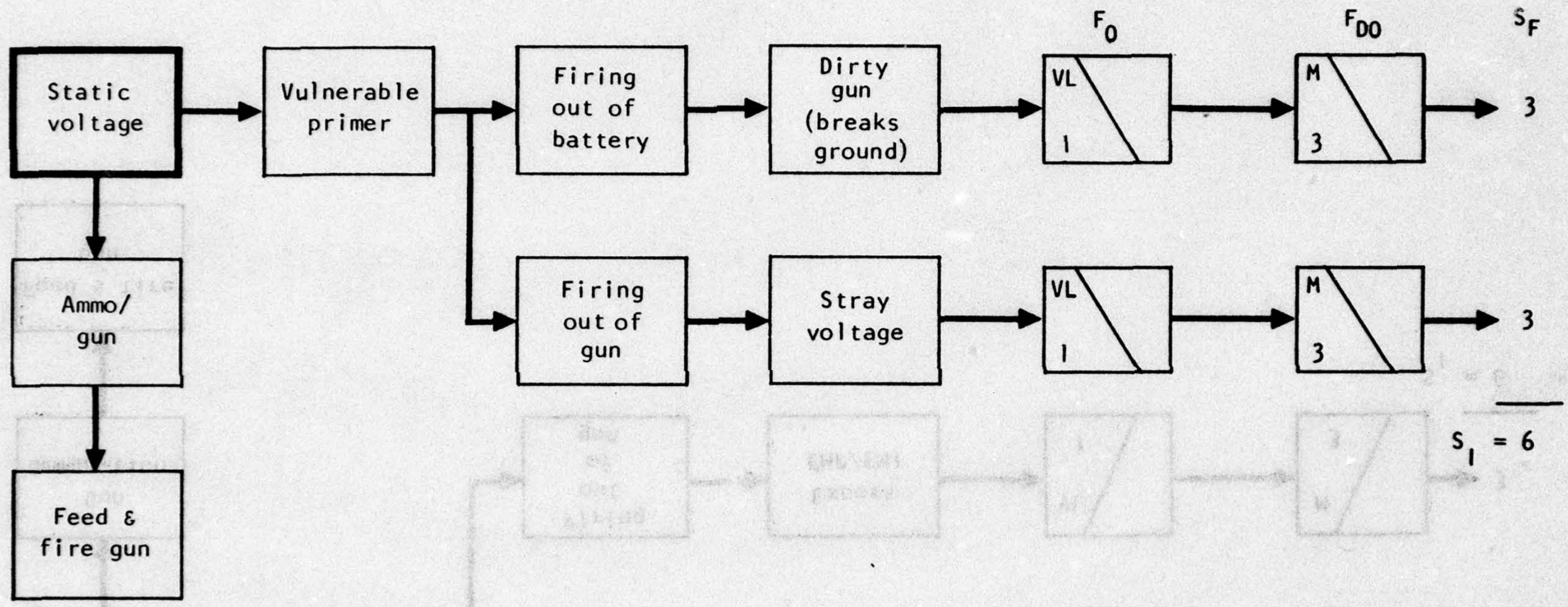


Figure 21. Static voltage.

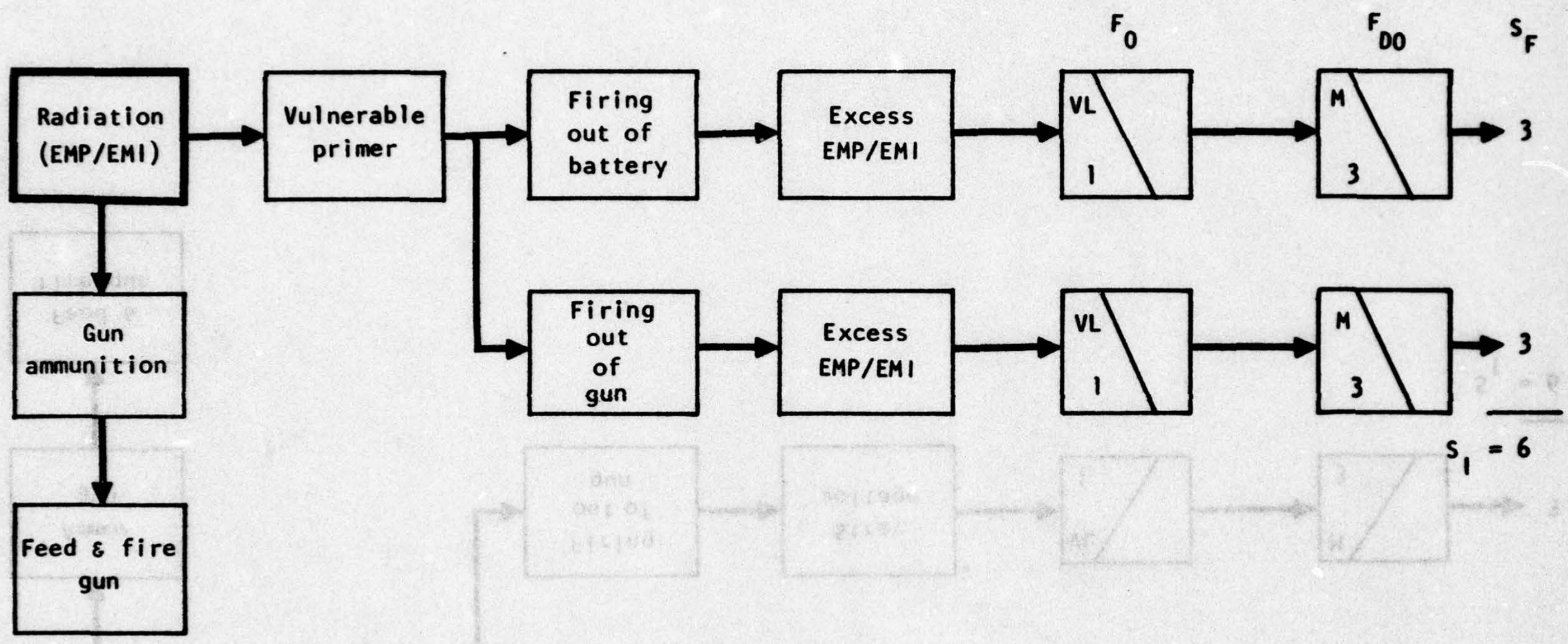


Figure 22. Radiation (EMP/EMI).

11. Enemy Fire (Figure 23)

a. Function and Component - The component is the gun system, and the function is to fire the gun.

b. Operative Condition - Combat.

c. Failure Mode - The modes are listed.

d. Specific Cause - The cause is projectile, fragment, or blast.

e. Severity Index - The S_I is 45. The values presented for F_O and F_{DO} are based on the assumption that combat conditions exist, not the possibility of combat occurring.

The result of this application of the methodology is a generic or baseline vehicle. Summation of S_I provides a numerical value of 315. This is further illustrated in Table 2.

METHODOLOGY APPLICATION

To evaluate a particular aircraft gun compartment configuration a complete set of the 11 generic general causes and a summary sheet is needed.

Each chart is completed in sequence, starting with gun failure and progressing through enemy fire. The evaluator must supply the value for F_O and F_{DO} for each possible outcome. Therefore, he must insure that all possible failure conditions have been accounted for and appear on the charts.

The values are supplied for the design under consideration based on test data, accident and incident reports, and engineering judgment. The generic baseline values can be used as a guide. Thus, if information indicates that the candidate design would not perform any differently than the generic or typical design, the values of F_O and F_{DO} would remain unchanged. If the likelihood of an occurrence has been altered by design changes, then the F_O would be altered accordingly. If a design change alters the type or extent of damage that can occur, then F_{DO} would be altered accordingly.

Once F_O and F_{DO} have been determined for each branch of a general cause, they are multiplied together to arrive at the S_F for that branch. The sum of the S_F's for all the branches of a general cause is the S_I for that general cause. The sum of the S_I's for all the general causes is the H_I for the entire gun system. This is the same procedure that was used to determine the baseline or generic aircraft and it is illustrated in Figure 12.

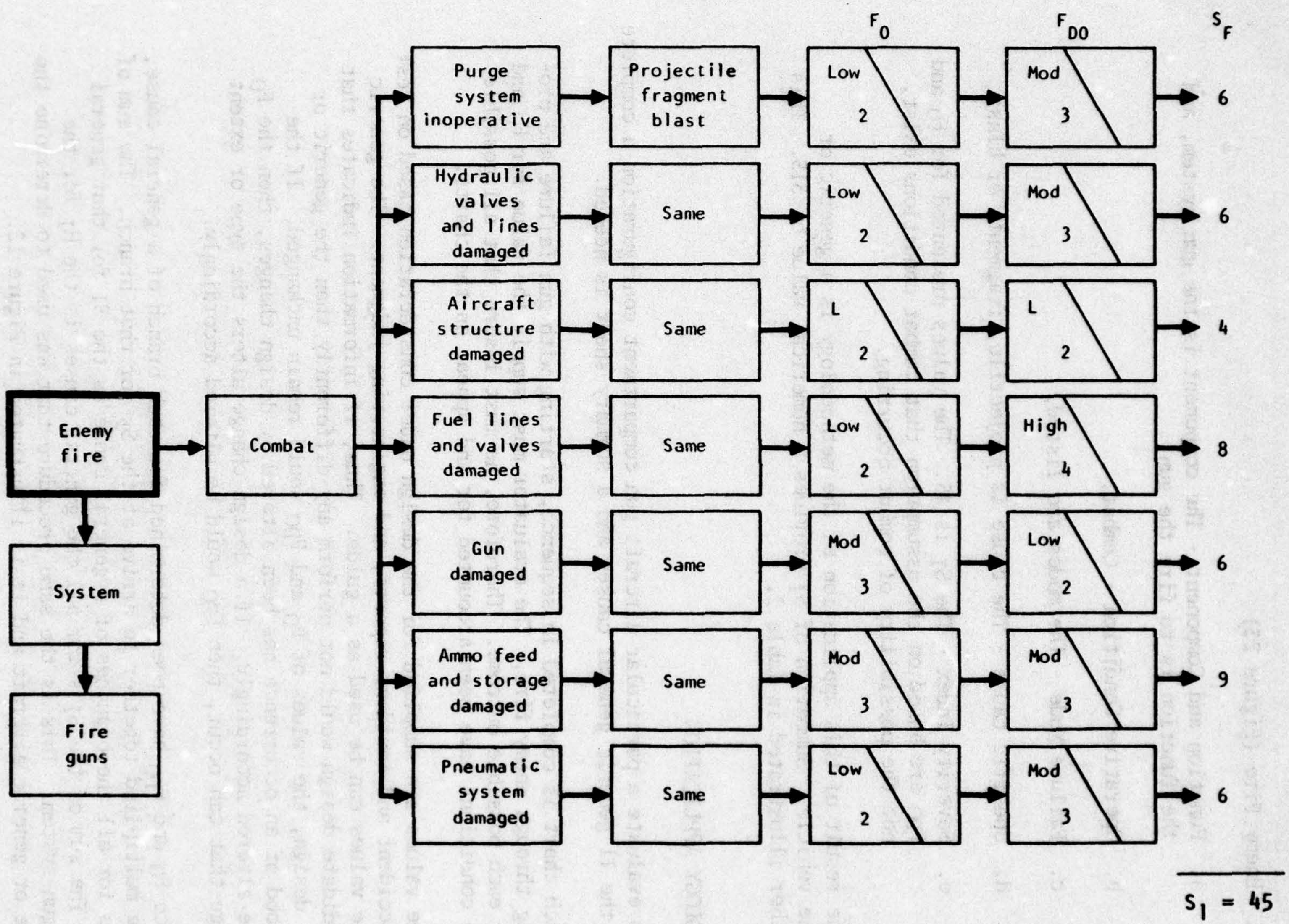


Figure 23. Enemy fire.

To verify the methodology and to thus evaluate its effectiveness, it was exercised against the A-10 and the F-15, two aircraft which are early in their operational life. The technique involved a comparison of the statistical results of the accident/incident data base with results of tests of the two aircraft, along with engineering judgment as to the applicability of the detailed causes to the specific design feature reviewed.

It should be noted that this methodology application does not consist of an evaluation of the gun systems in the A-10 and the F-15. Design requirements and mission effectiveness were not considered. Instead, it is an evaluation of the possibility of occurrence of the gun compartment hazards associated with fire and explosion, as compared to a generic vehicle obtained from previous U.S. Air Force and U.S. Navy accident/incident data, with the results tempered by engineering judgment. As such, it offers an important tool to the designer who can apply the principles early in the conceptual design stages of future gun-carrying aircraft.

Neither the A-10 or the F-15 have accumulated sufficient operational experience to affect the accident/incident data base. For statistical evidence of their gun-firing experience, test data were used. The value of this process could be considerably enhanced if frequent updates were made of the A-10 and F-15 operational experience so that actual occurrences could be tabulated and compared to previous estimates and test results.

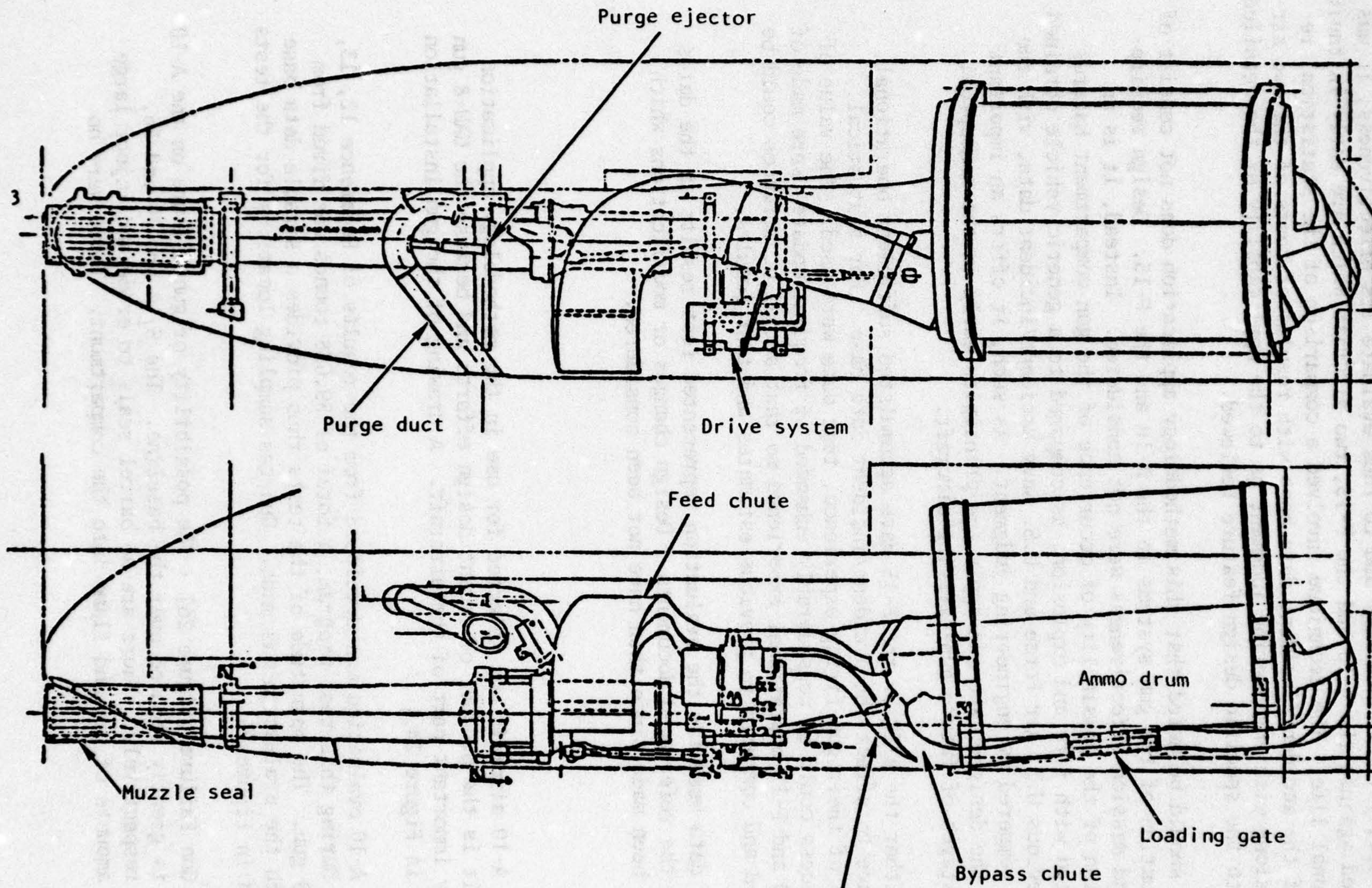
The data used for the evaluation represented test results at the dates shown in the referenced documents. Design changes or modifications which may have been made since then have not been considered.

A-10

The A-10 aircraft was selected for use in the methodology application because it is the product of recent design efforts and because the GAU-8 gun is a very important part of the aircraft. A drawing of the gun installation is shown in Figure 24.

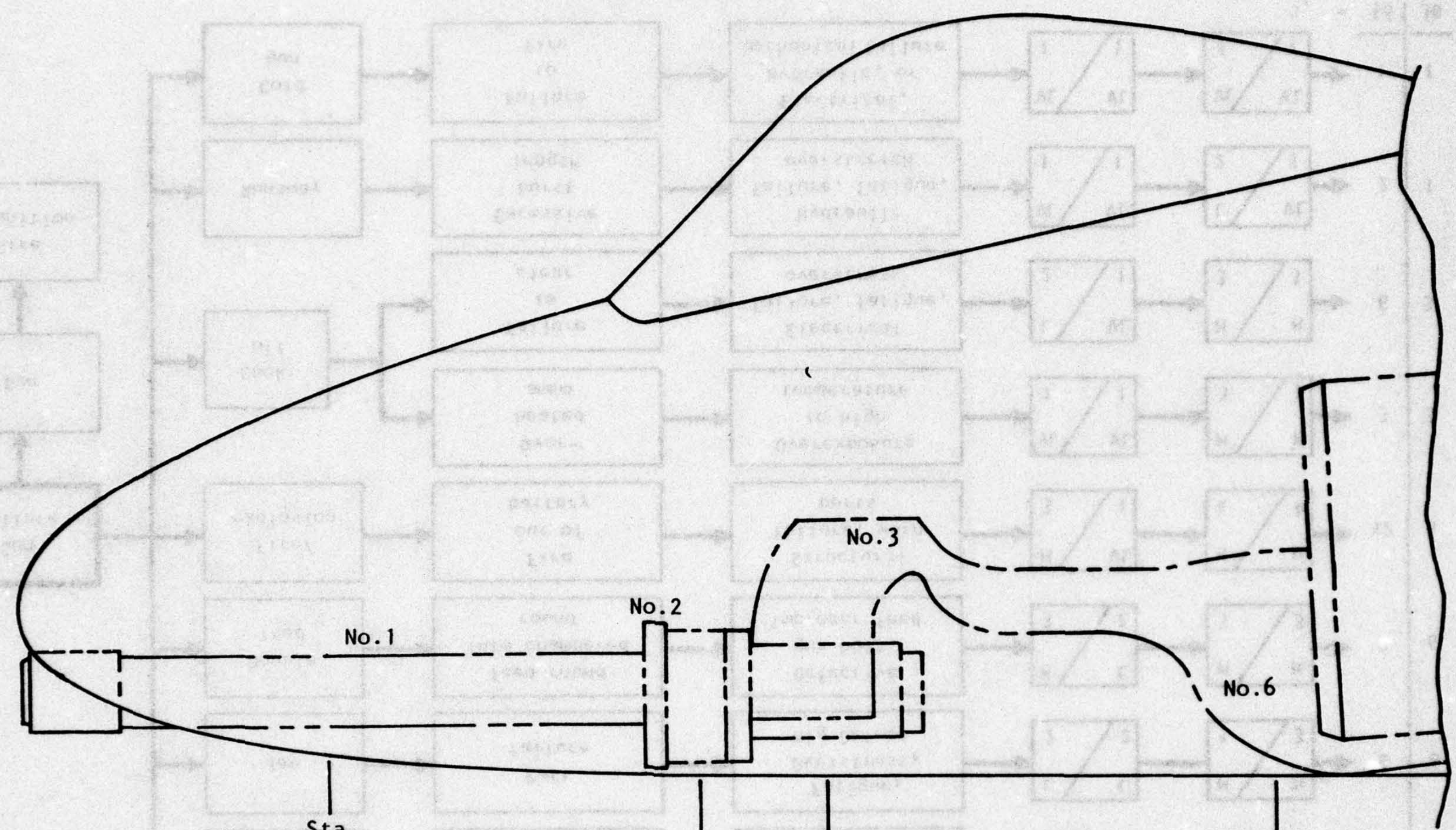
The A-10 evaluation was developed from the results of Reference 12, 13, and 14. During this test program, a total of 59,638 rounds was fired from the GAU-8 gun. The magnitude of the tests thus provides a sizable data base from which the evaluation was made. Gun-gas sampling locations for the tests are shown in Figure 25.

1. Gun Failure (Figure 26) - The possibility of gun failure on the A-10 is greatly reduced over the baseline. The S_I's are 30 and 56, respectively. There are no barrel seals to erode and inject large amounts of gas and flame into the compartment. There were no



Courtesy of Fairchild Republic Co.

Figure 24. GAU-8/A 30 mm gun system installation - A-10.



Courtesy of Fairchild Republic Co.

Figure 25. Location of gun gas detectors - A-10.

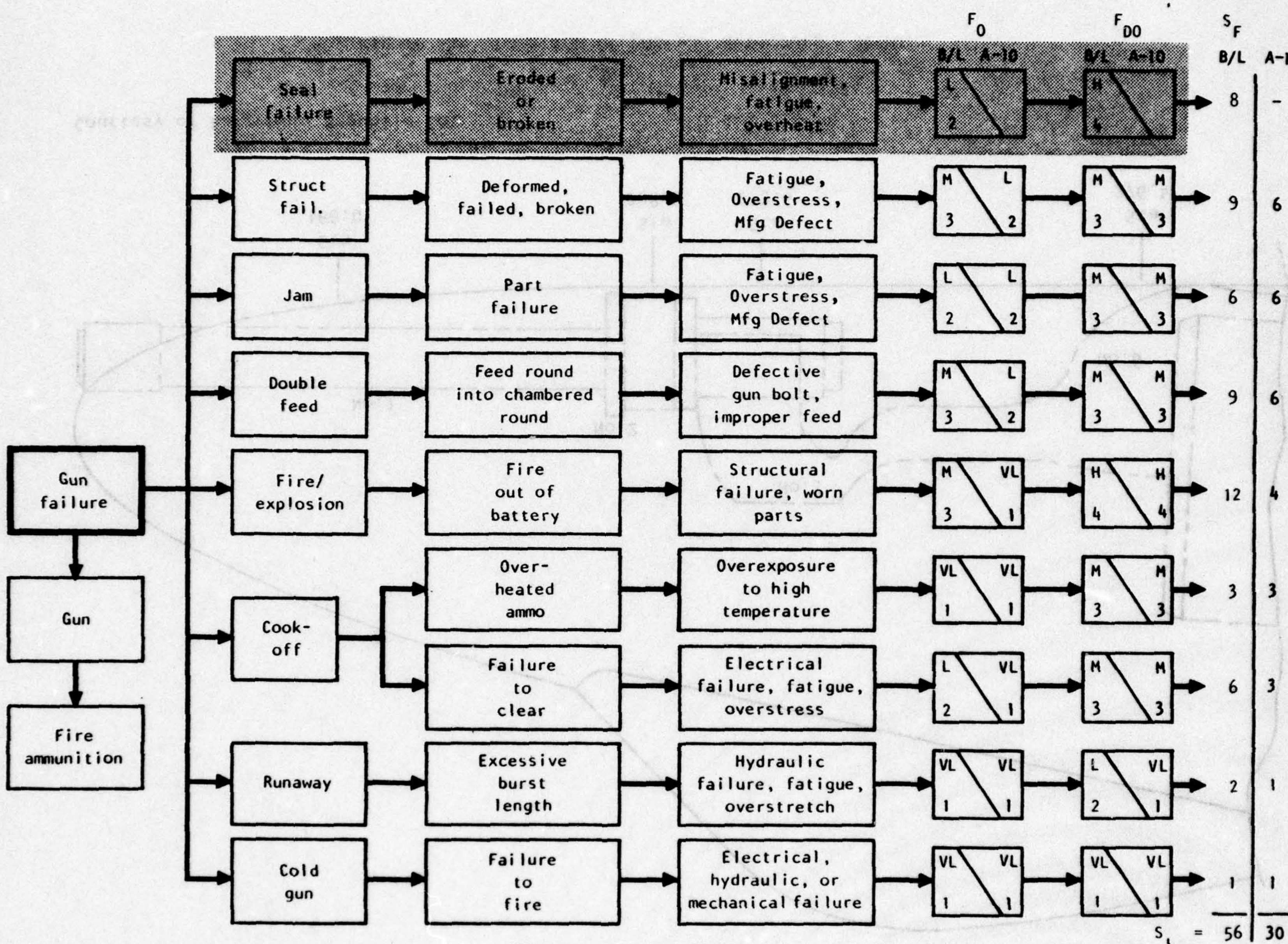


Figure 26. Gun Failure.

structural failures, jams, double feeds, or explosions caused by the gun during the test program. However, the maintenance records indicate that some potential problems were avoided by proper maintenance. Thus, some possibility of these occurrences remains. The runaway gun possibility of damage is reduced because it is believed that the A-10 can fire a full complement of ammunition in one burst without damage to gun or aircraft.

2. Gun Drive Failure (Figure 27) - The S_I 5, slightly reduced from the baseline.

3. Feed Failure (Figure 28) - The S_I is 30, reduced from 42 for the baseline. There was one chute failure during the test, however, the part was redesigned and it would not be expected to recur. With high-speed firing of 30mm ammunition, some possibility of failure remains.

4. Purge Failure - S_I is zero. Purge system deleted from aircraft. During tests, the gas concentration never exceeded 56 percent of the LFL and the overpressure within the bay never exceeded 1.0 psi. A relief door is structured to open at 2 psi overpressure.

5. Ammunition Failure (Figure 29) - S_I is 42, baseline S_I 50. Only slight reduction. There were four ammunition failures during testing. Failure to fire is eliminated since the GAU-8 continues to feed even if the chambered round fails to fire.

6. Aircraft Structural Failure (Figure 30) - S_I is 11, baseline 13. There is a slight reduction in the muzzle clamp failure because the gun muzzles are well outside the fuselage. With buried muzzles such as many aircraft have, a small deviation in alignment, such as might occur during partial muzzle clamp failure, could throw projectiles through aircraft structure. This would be difficult in the A-10. There were failures of the gun mount support structure during the test program, but redesign reinforced the area so that there should be no recurrence.

7. Aircraft Systems Failure (Figure 31) - S_I is 14, baseline 16. There were no systems failures in the test program. The electrical systems possibility is reduced because the A-10 contains an interlock control circuit so that any one electrical circuit failure cannot cause inadvertent firing.

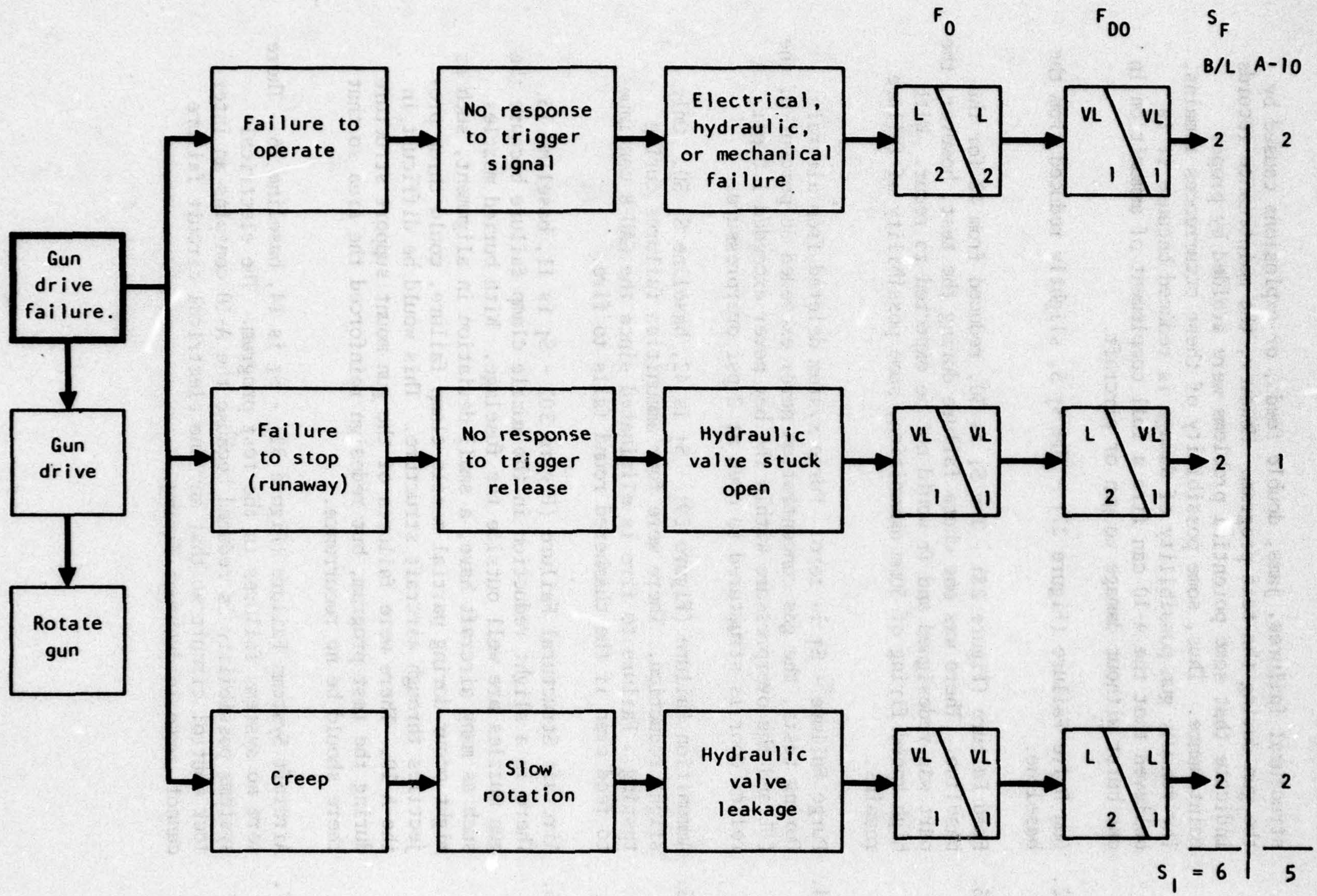


Figure 27. Gun drive failure.

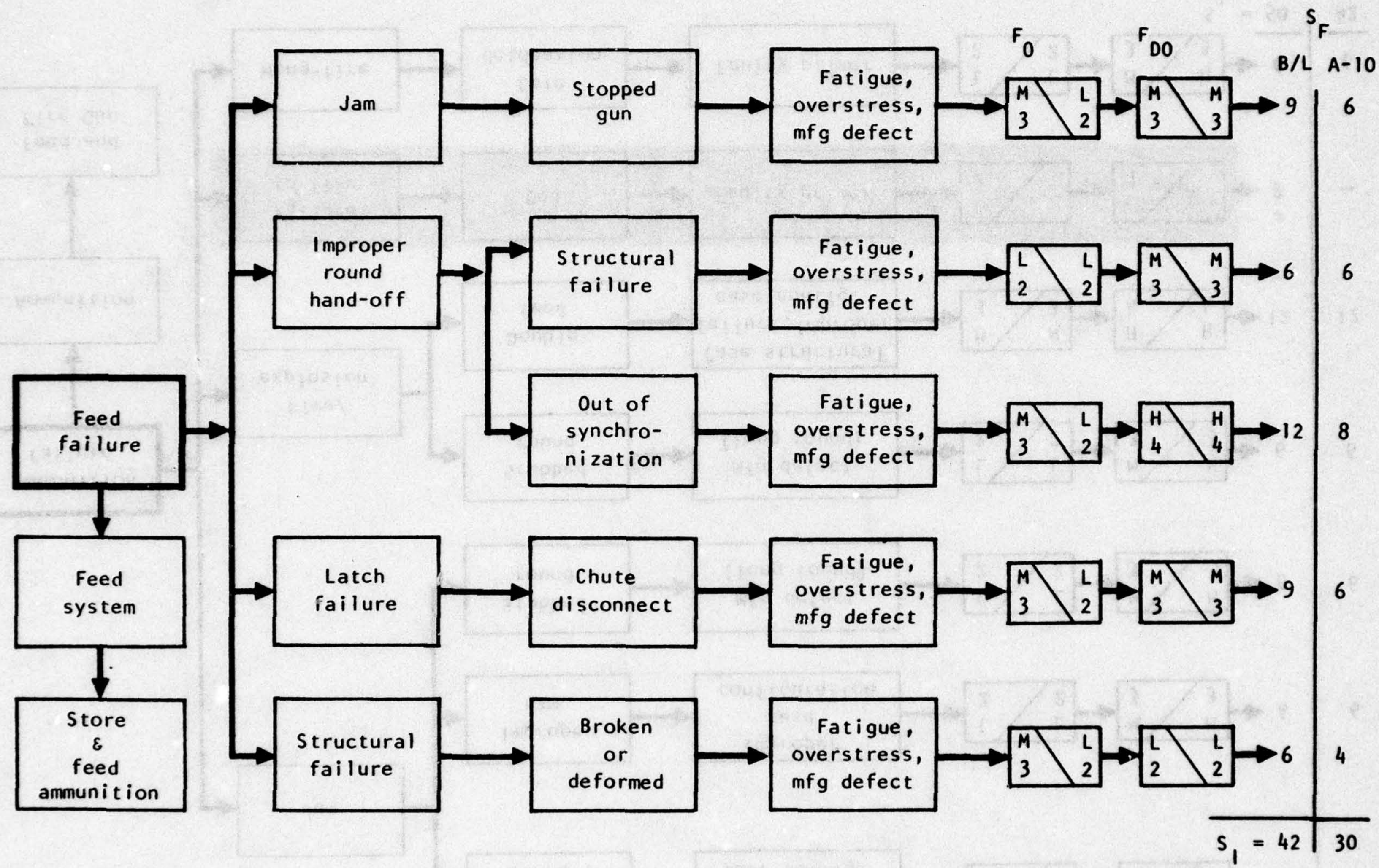


Figure 28. Feed failure.

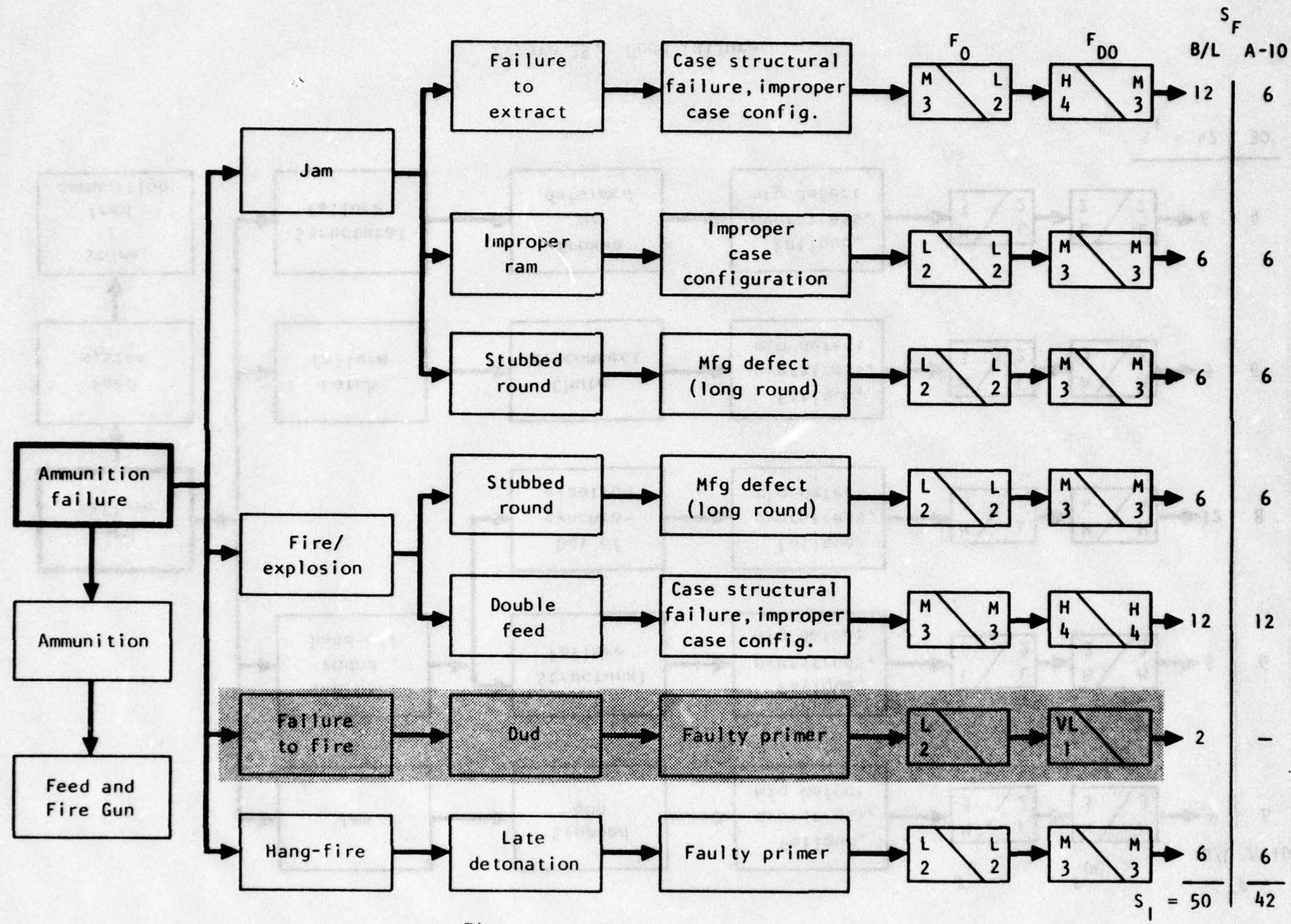


Figure 29. Ammunition failure.

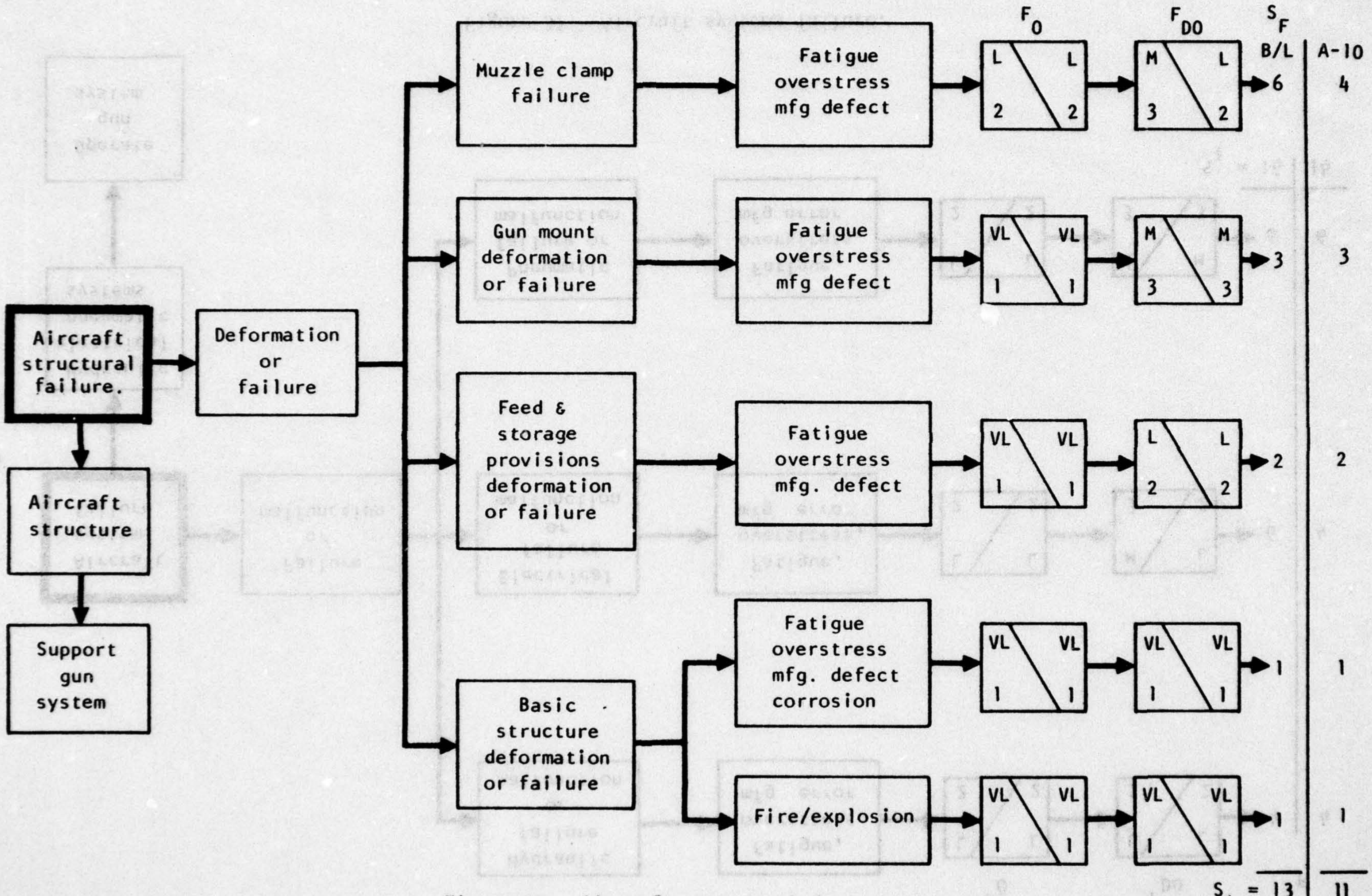


Figure 30. Aircraft structural failure.

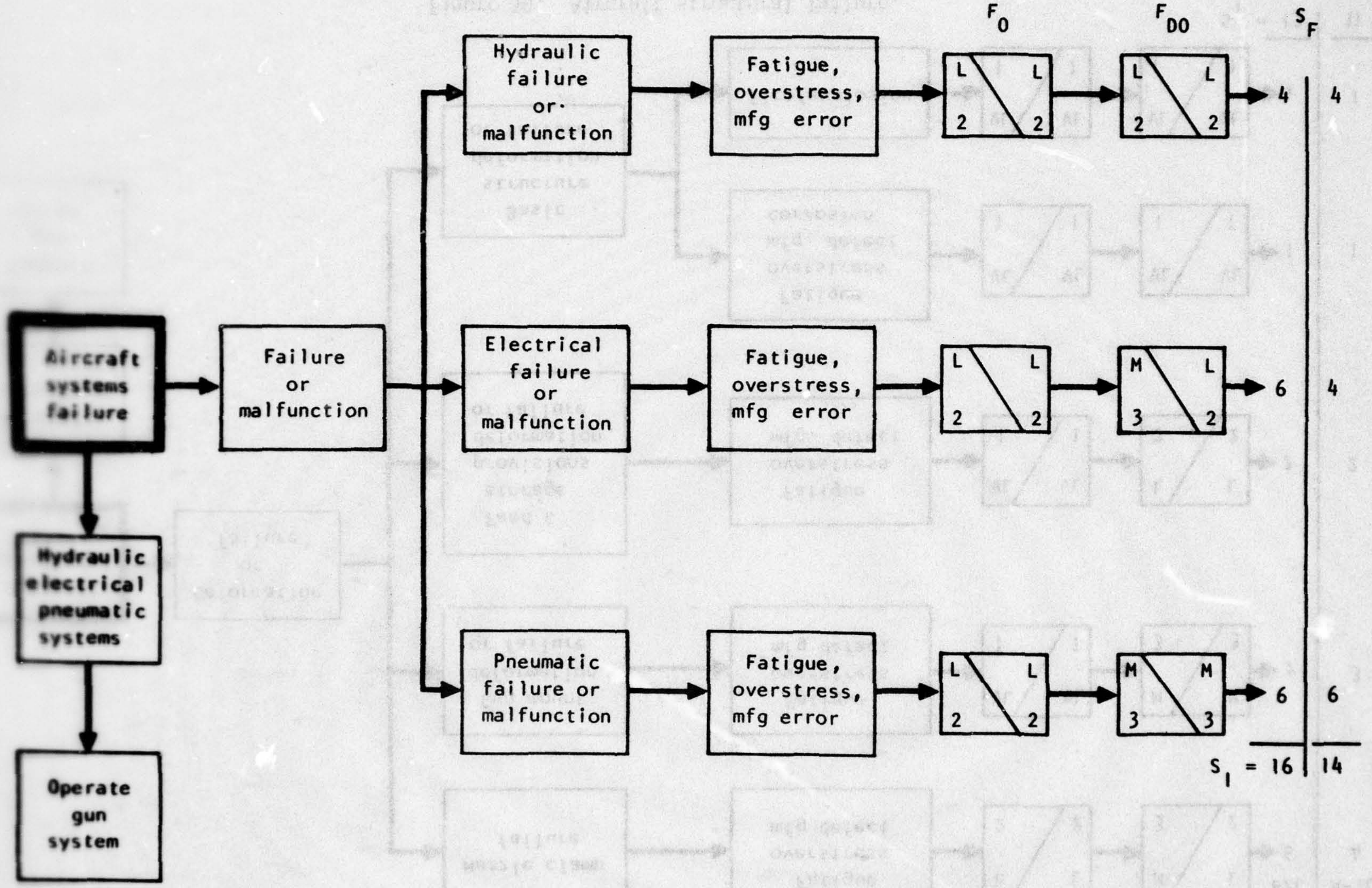


Figure 31. Aircraft systems failure.

8. Personnel Error (Figure 32) - S_I is 24, baseline 41. Unsafe assembly has been reduced because there were no failures attributable to this in the test program and it is believed that good procedures and training will continue to hold the possibility low. Unsafe operation is reduced further because of "hot trigger" and "gun unsafe" lights added to the cockpit. The A-10 is designed for low-altitude, low-speed operation and is unlikely to be operated beyond its limits. If it is inadvertently so operated, the rugged nature of its construction should reduce the possibility of damage to very low.

9. Static Voltage (Figure 33) - S_I is 6, baseline 6. The GAU-8 ammunition is percussion-fired and it is questionable whether it can be detonated by stray voltage. However, tests are underway to determine whether it can be set off by other than the firing pin (Reference 16). Pending completion of the tests, a slight possibility of occurrence is carried.

10. Radiation (EMP/EMI) (Figure 34) - S_I is 6, baseline 6. The possibility is similar to that of static voltage -- it is questionable whether the percussion primer can be fired this way. Pending results of analysis or test, the possibility remains.

11. Enemy Fire (Figure 35) - S_I is 27, baseline 45. Several features reduce the possibility of damage from enemy fire. The purge system is deleted, however, the ejector remains unpowered and a small possibility of damage could reduce or stop its capability to exhaust breech gas. An overtemperature warning system is installed, bay air temperature is monitored, and a fire extinguishing system is installed. These reduce the possibility of damage from a hydraulic hit to very low. There are no fuel lines or valves in the bay. The pneumatic system possibility of damage is reduced because the air reservoir is made of nonshatterable steel.

12. Conclusion - The sum of the S_I's, the H_I is 195 (Table 2), considerably below the baseline index of 315.

F-15

The F-15 also offered the opportunity to exercise the developed methodology against an aircraft of recent design. The M61 gun is an integral part of the system. However, the gun has had a long operational record and is expected to be correspondingly improved over earlier models. A drawing of the F-15 gun installation is shown in Figure 36. Figures 37 and 38 show the difference between the early design, which included a purge system and the later design in which the purge system was deleted because of favorable test results. Figure 39 shows the location of gas sensors during the referenced tests.

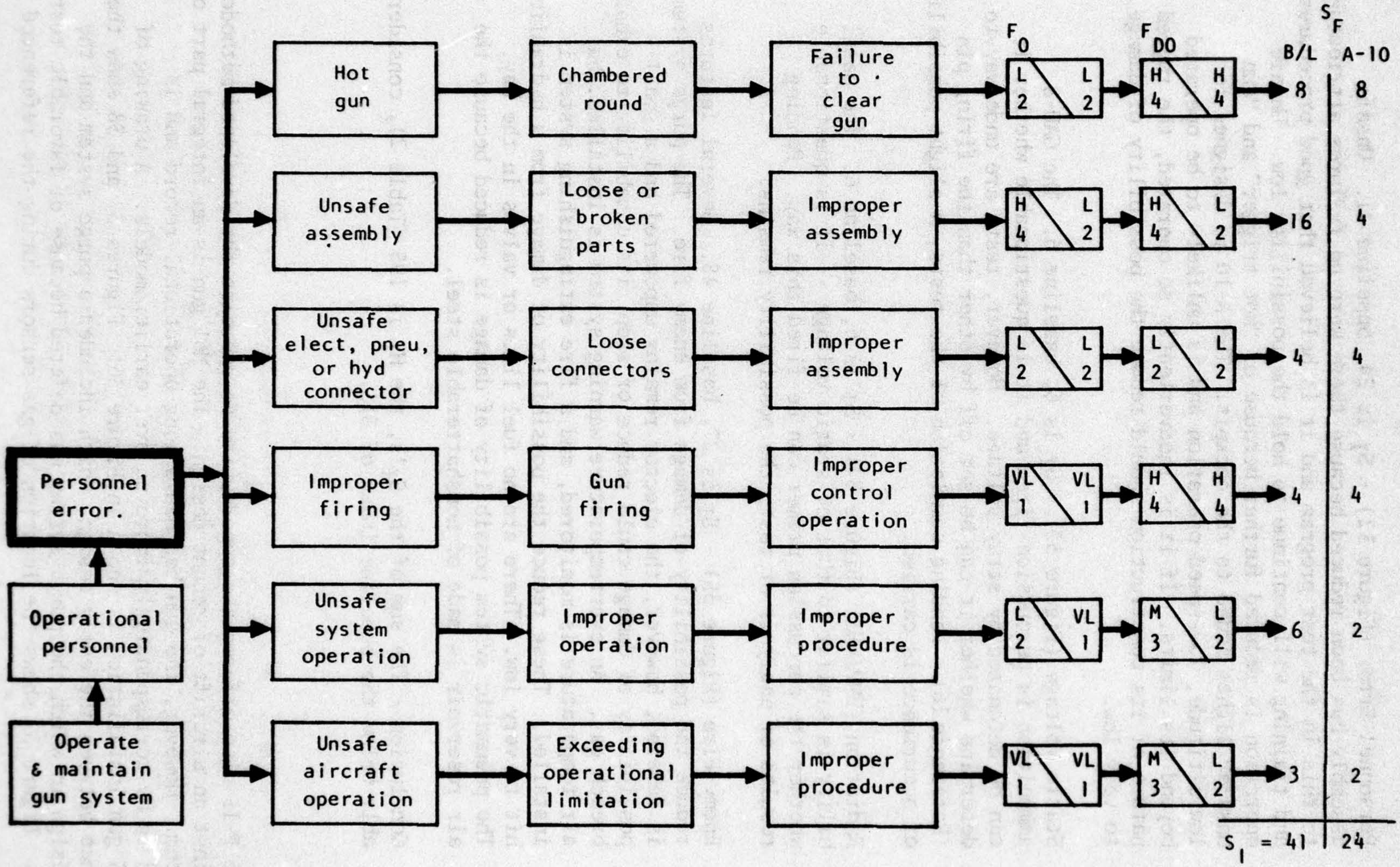


Figure 32. Personnel error.

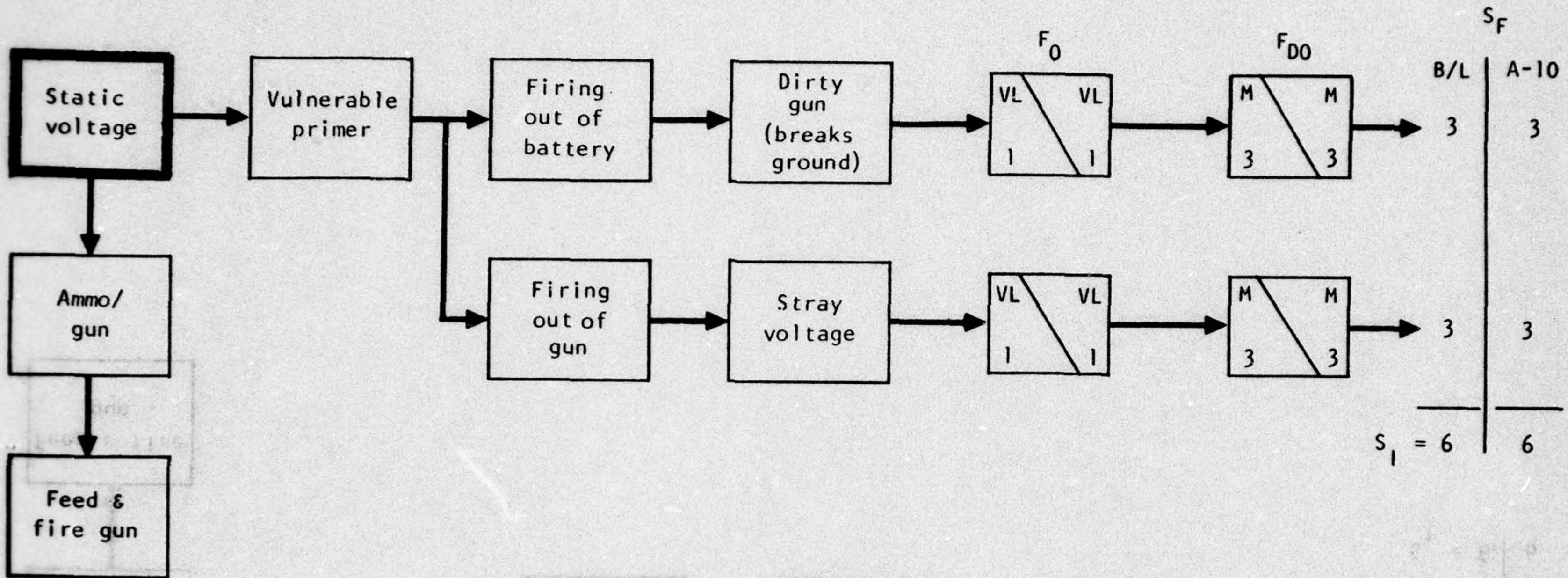


Figure 33. Static voltage.

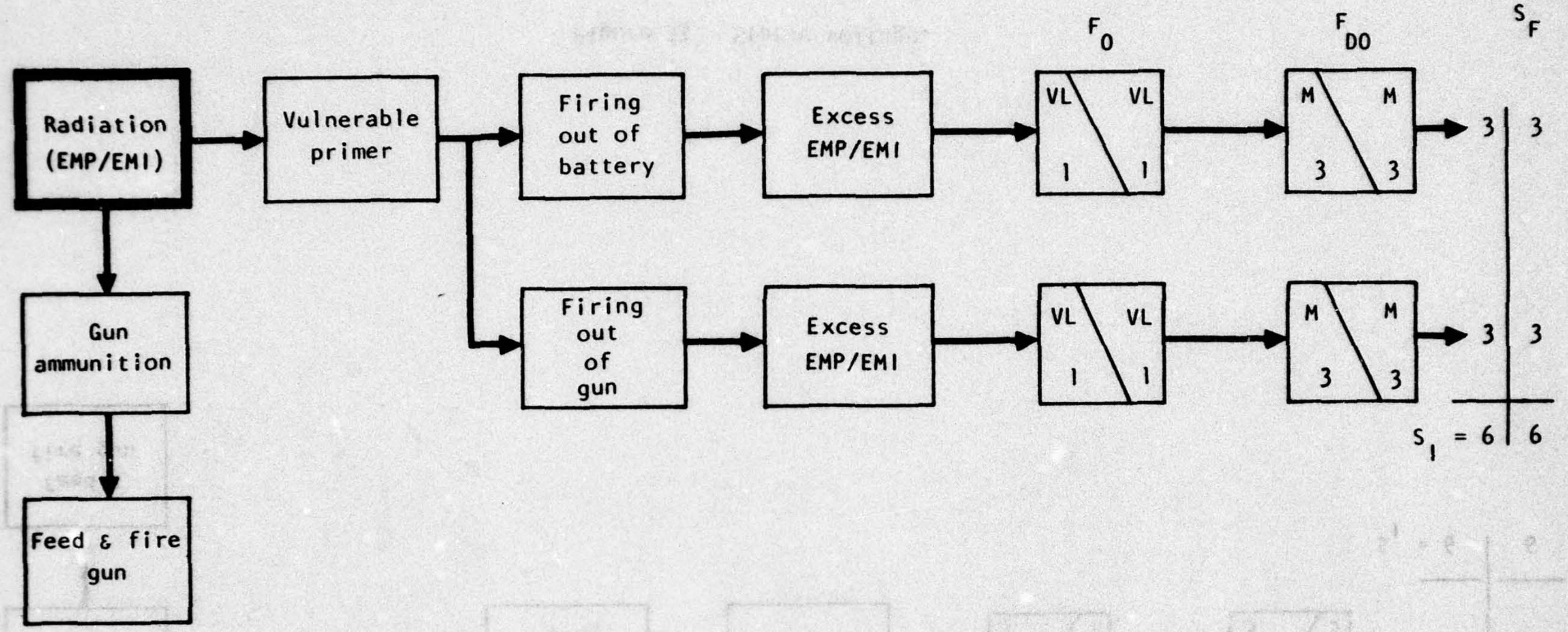


Figure 34. Radiation (EMP/EMI).

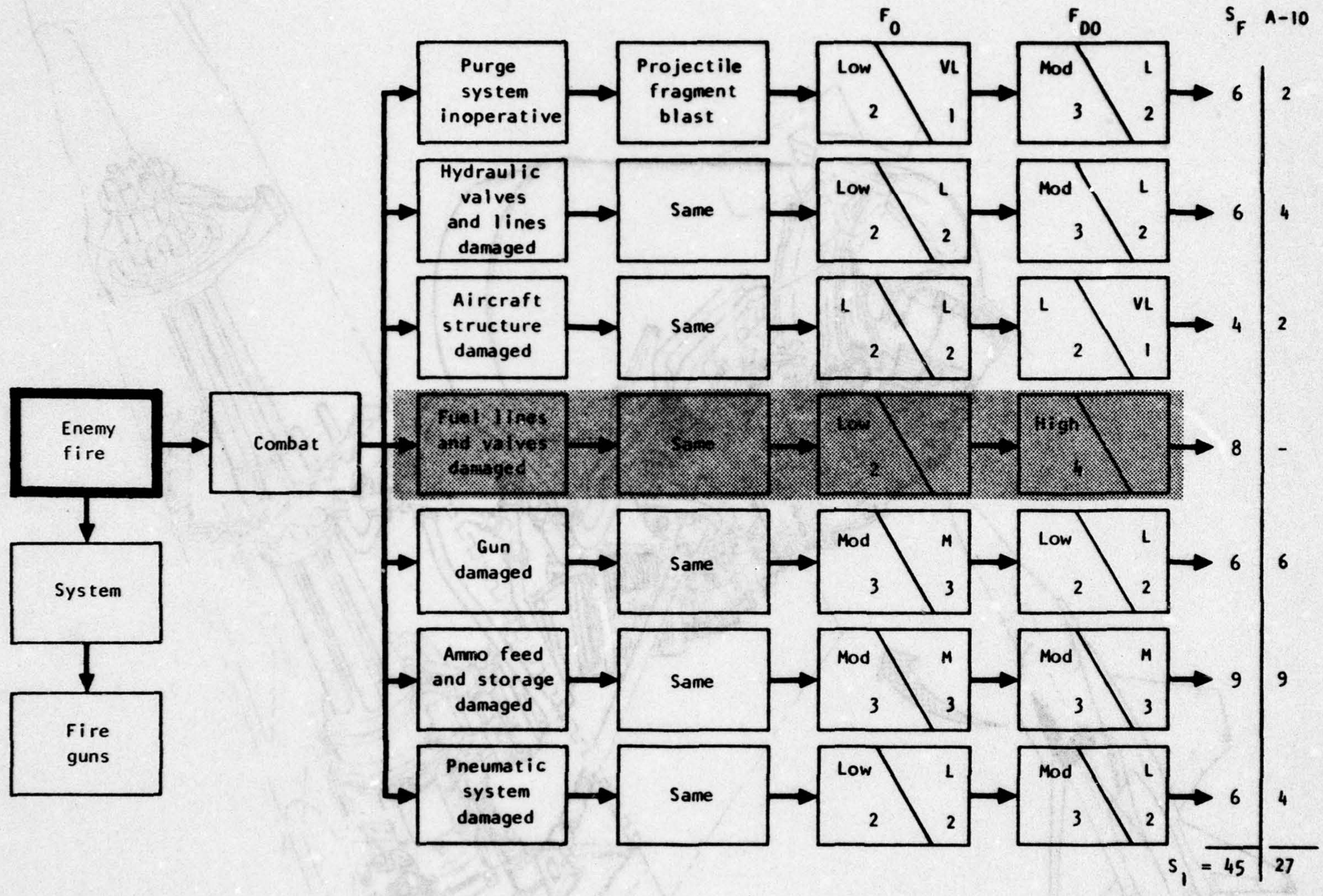


Figure 35. Enemy fire.

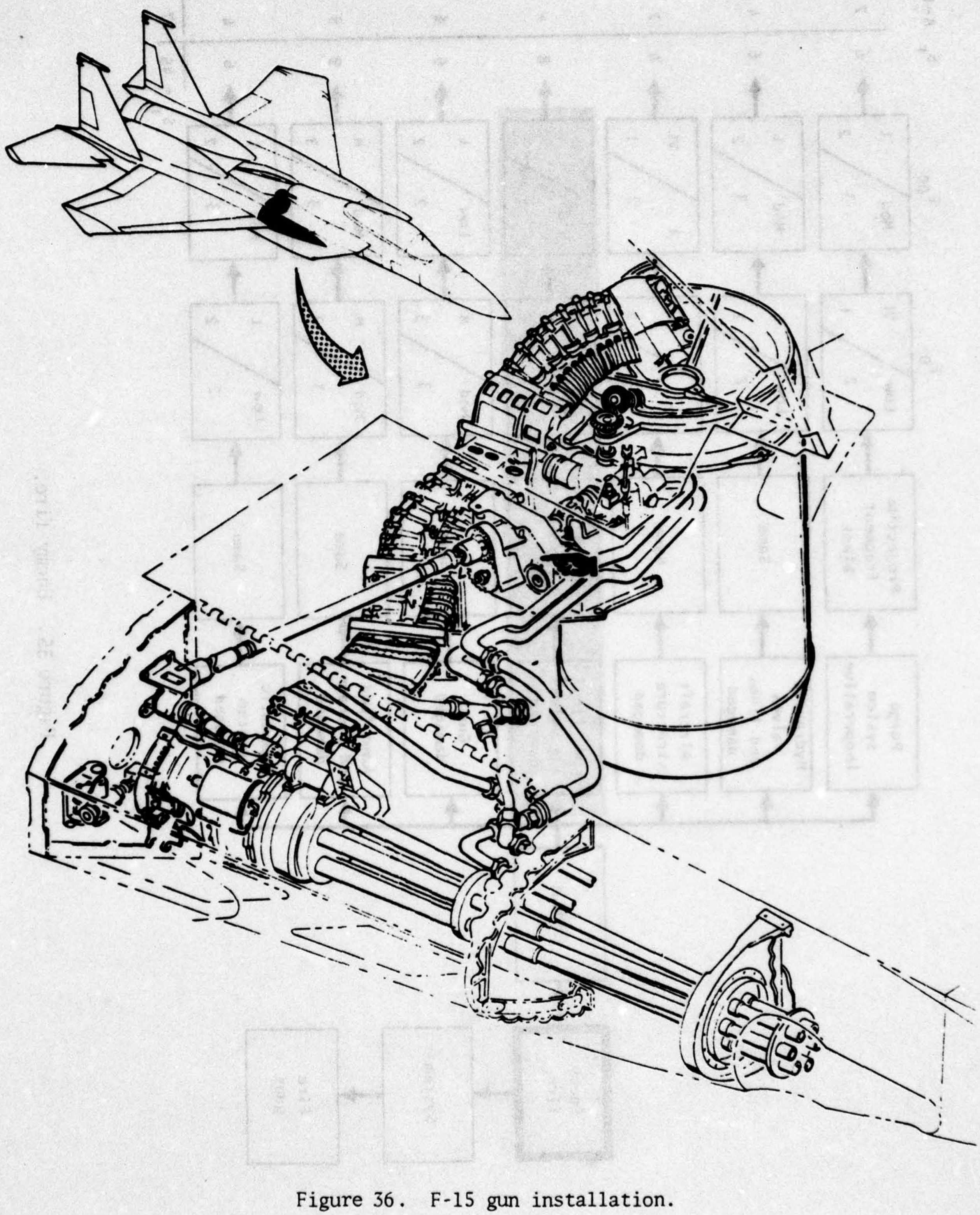
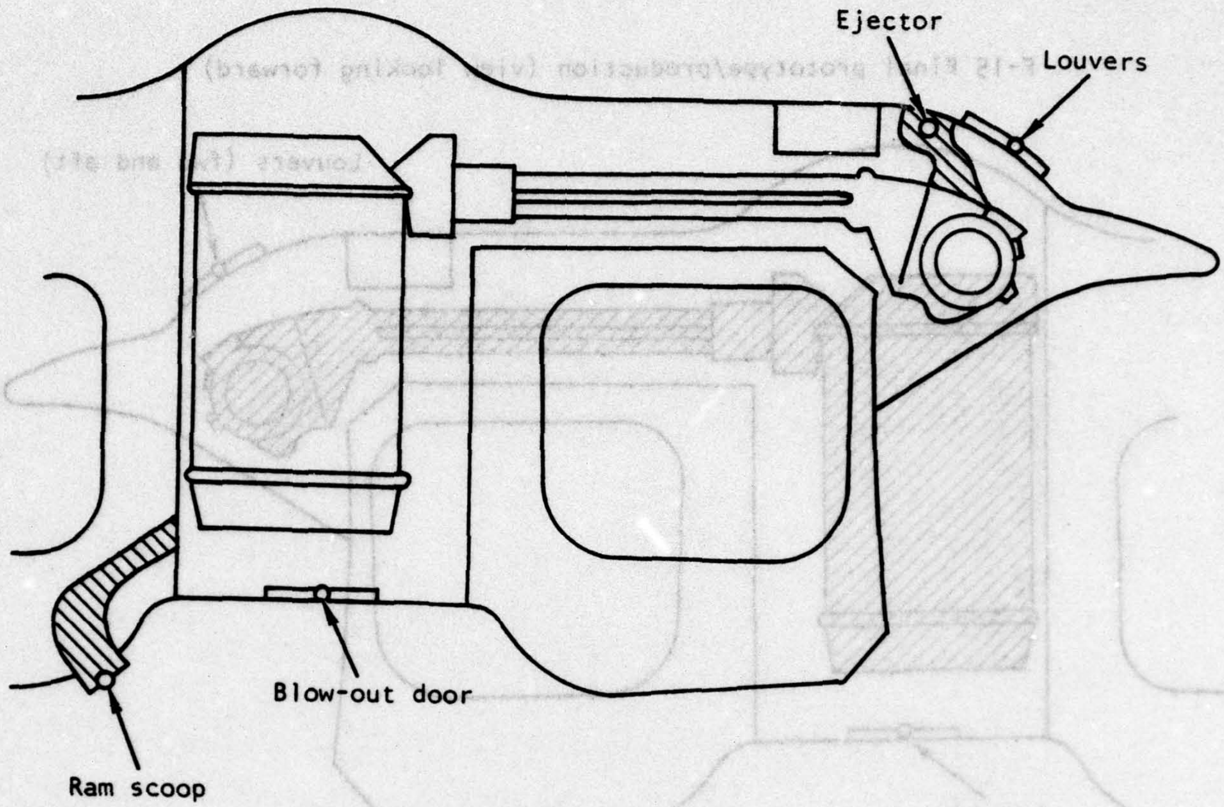


Figure 36. F-15 gun installation.

F-15 early prototype (view looking forward)



Volume = 39 cu ft

Louvered area = 60 sq in.

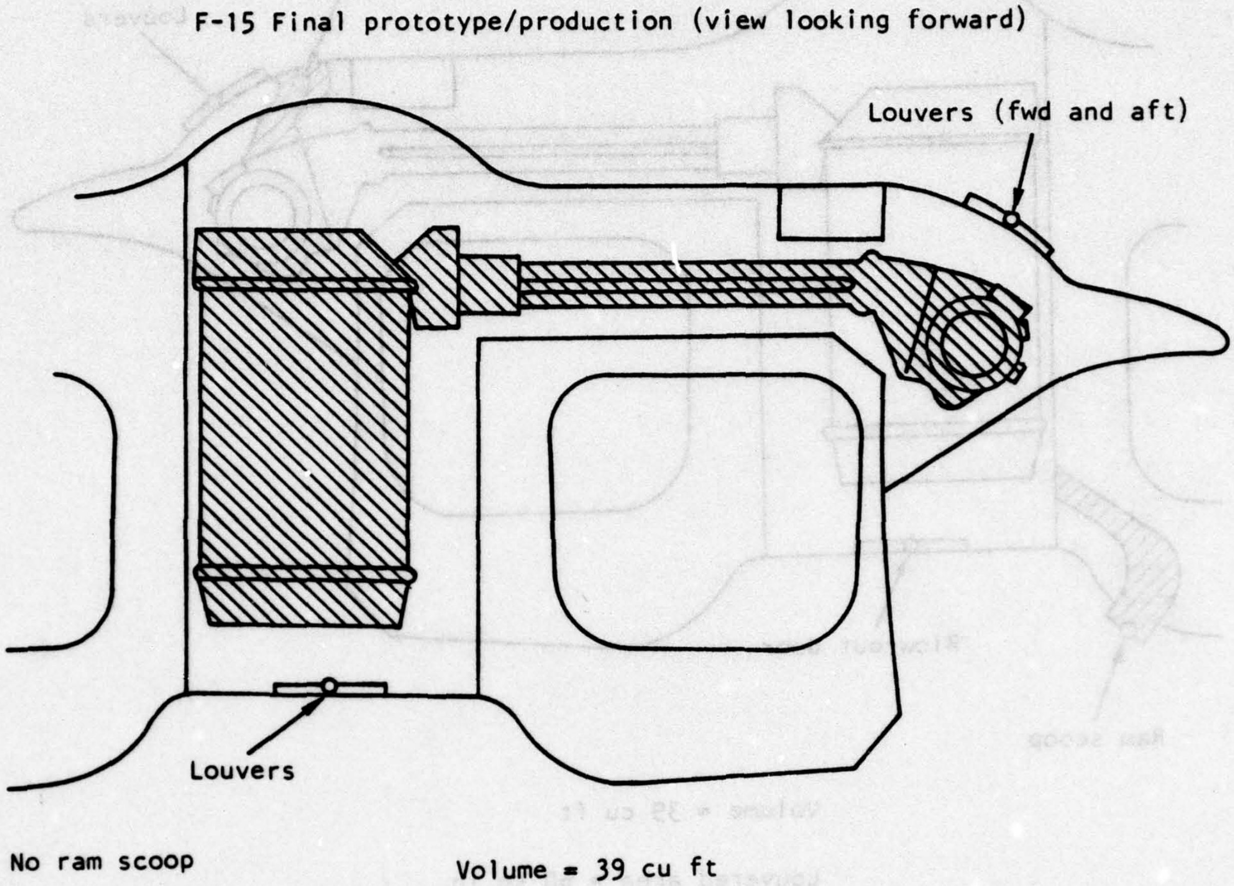
Vent ratio = 1.07

Inlet area:

20 sq in. requested for 150% LEL
15 sq in. final configuration

Courtesy of McDonnell Aircraft Co.

Figure 37. F-15 purge system.



Volume = 39 cu ft

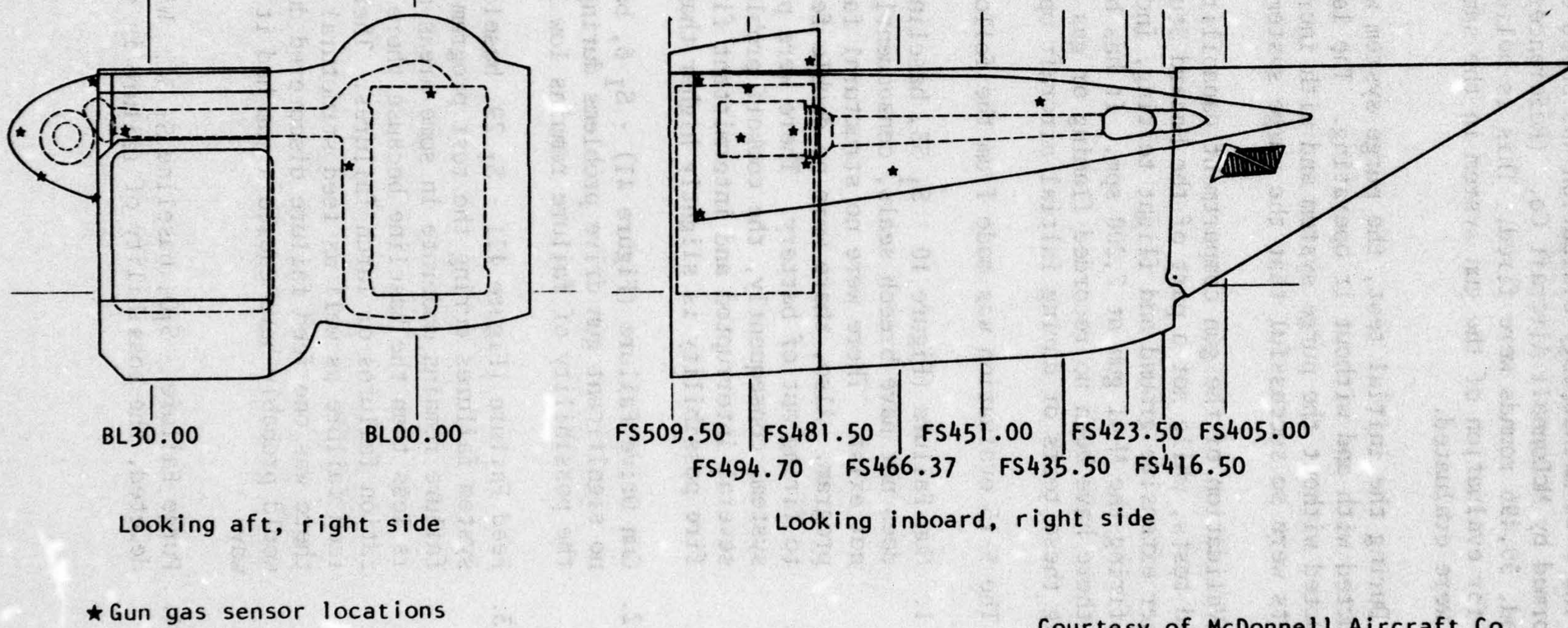
Louvered area = 195 sq in.

(120 sq in. above breech)
(35 sq in. at fwd barrels)
(40 sq in. in ammo bay)

Vent ratio = 3.47

Courtesy of McDonnell Aircraft Co.

Figure 38. F-15 gun installation - purge system deleted.



Courtesy of McDonnell Aircraft Co.

Figure 39. F-15 gun bay instrumentation.

The F-15 methodology evaluation was based on three sets of ground tests performed by McDonnell Aircraft Co. (References 11, 17, 18). During this period, 50,496 rounds were fired. This is believed to be a creditable data base for evaluation of the gun system in the same way the baseline and the A-10 were evaluated.

During the initial test, the purge system was installed and tests were conducted with and without it operating. The last two tests, however, were conducted without the purge system and with increased vent area. The results were so successful that the purge system was permanently deleted.

Validation of the gun compartment capability established during these ground tests, while not a part of the Hazard Study, has been established by further extensive ground and flight testing, including the current flight test firing the M-61 gun at 7,200 spm. It has been reported (Reference 19) that there have been no recorded flaming or gas explosions in the gun bay during these tests or during initial aircraft operational experience.

The F-15 evaluation was made from the following:

1. Gun Failure (Figure 40 - S_I 35, baseline S_I 56. The M-61 gun does not have breech seals, consequently, this possibility does not exist. There were no structural failures during the test program. Also, there were no double feeds or fire/explosions due to firing out of battery. There were problems with the clearing system, consequently, the cookoff problem remains. There were several interrupted and intermittent firings so the failure to fire possibility is slightly higher than the baseline.

2. Gun Drive Failure (Figure 41) - S_I 6, baseline S_I 6. There were no significant gun drive problems during testing, consequently, the possibility of failure remains low like the baseline.

3. Feed Failure (Figure 42) - S_I 29, baseline S_I 42. There were feed system failures during the test program so the possibility of failure remains moderate in some areas although the overall index is less than the baseline because there were no out of synchronization failures or latch failures. There were, however, jams due to feed failure as well as feed structural failure. In addition, there was one feed failure discovered during maintenance that would probably have caused a jam had it not been discovered this way.

4. Purge Failure - S_I0, baseline S_I 34. With the purge system deleted, the possibility of failure is reduced to zero.

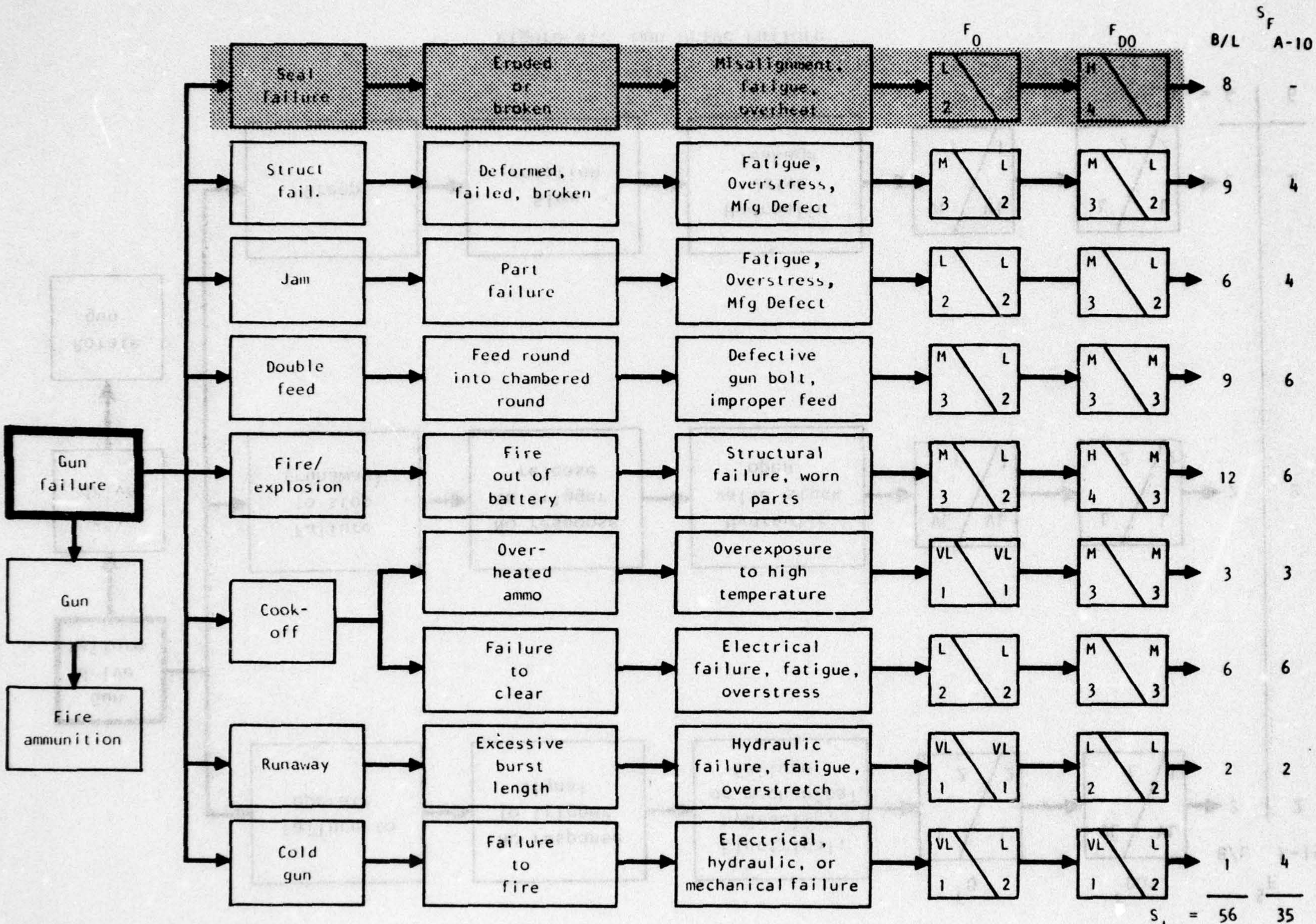


Figure 40. Gun Failure

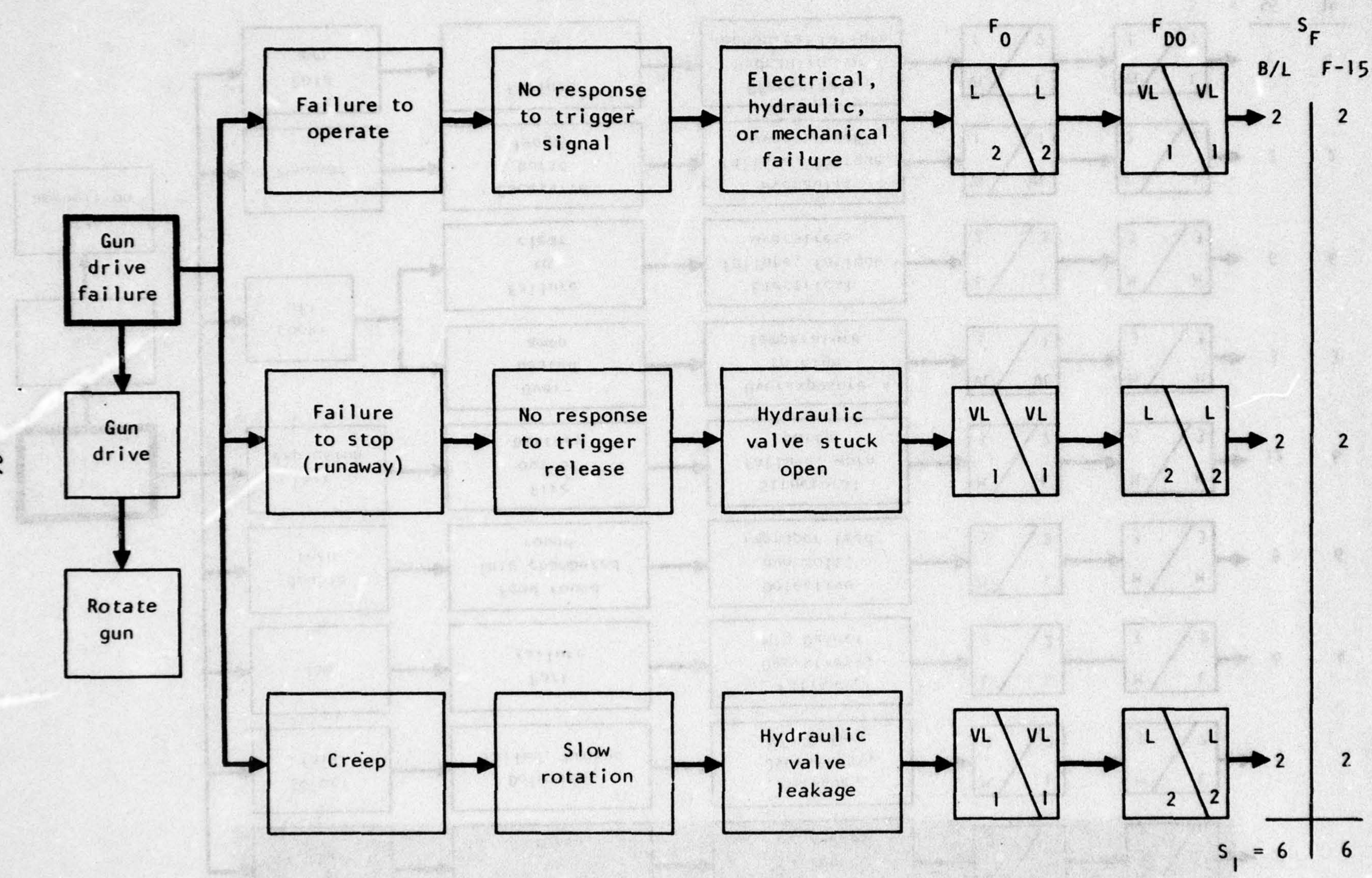


Figure 41. Gun Drive Failure

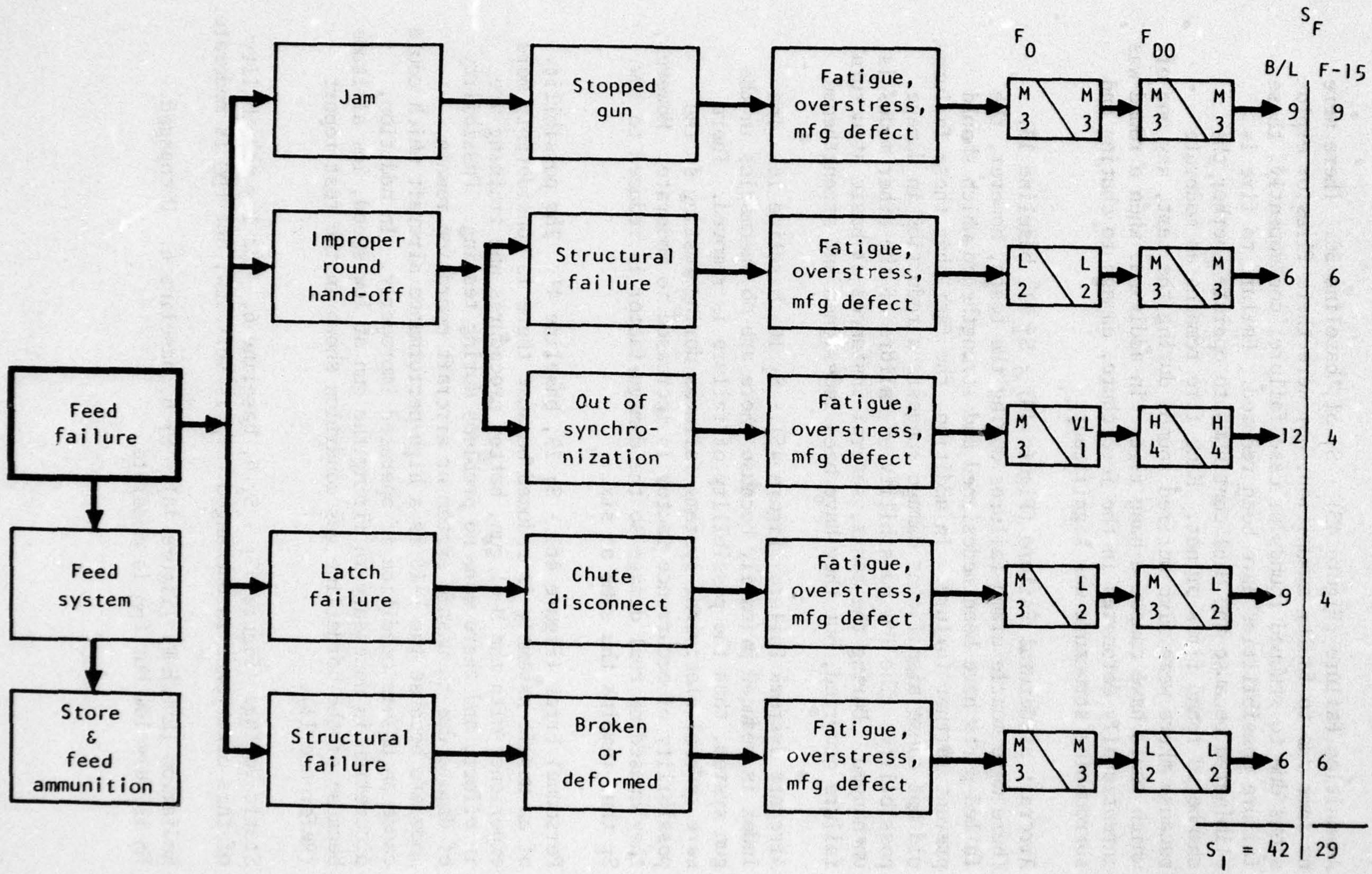


Figure 42. Feed failure.

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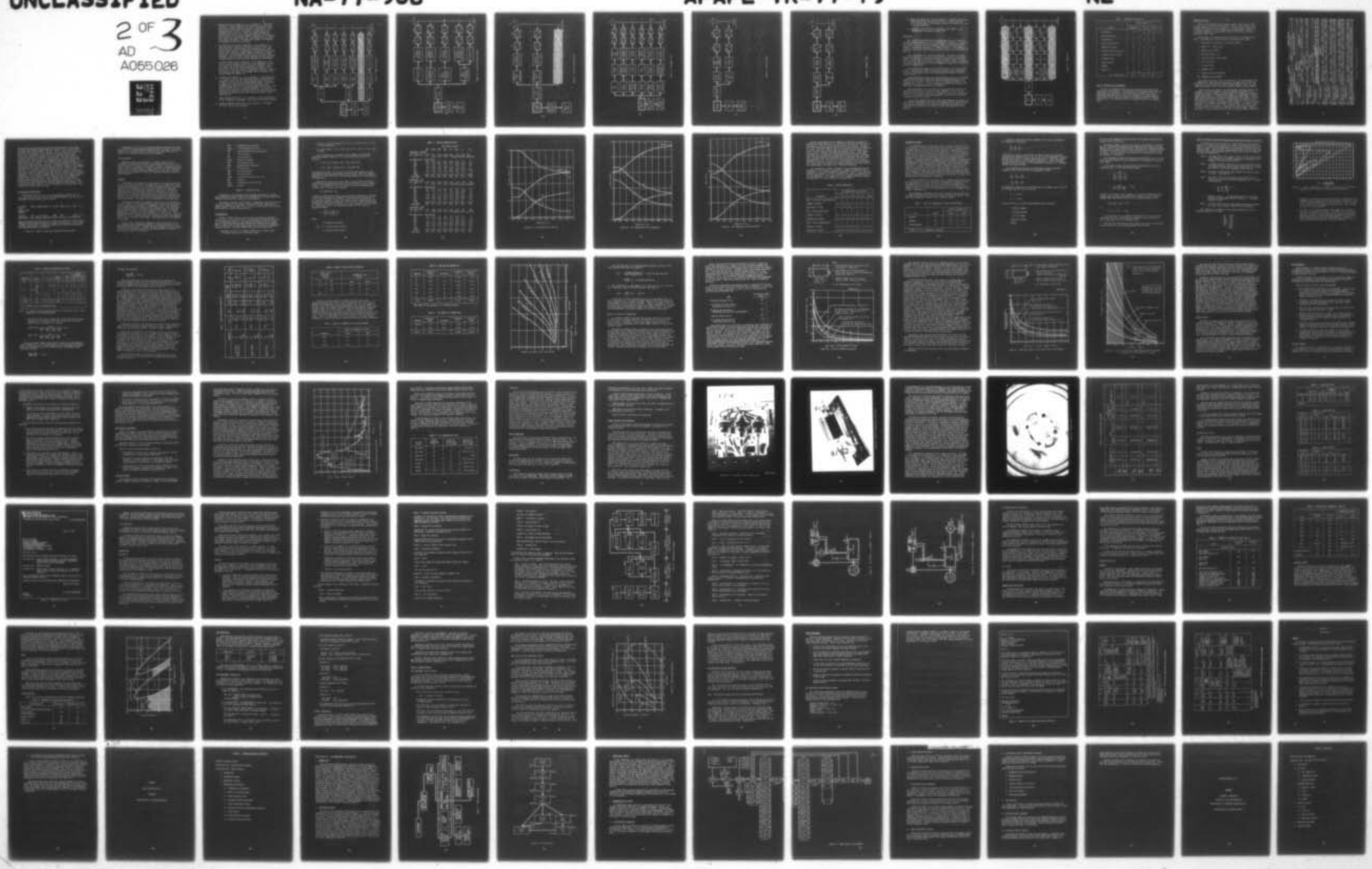

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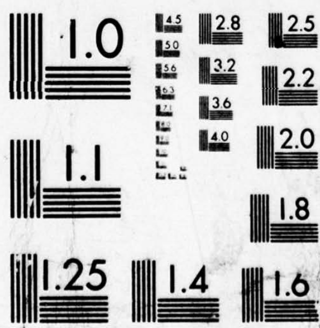


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

5. Ammunition Failure (Figure 43) - S_I 31, baseline 50. There were no jams due to faulty ammunition, nor were there fires or explosions due to stubbed rounds or case failure; consequently, these failure possibilities have been reduced. Failure to fire is eliminated because the M-61 continues to operate whether the chambered round fires or not. Hang fire remains as moderate because there were five unfired rounds during the test, any one of which could have caused a hang fire. In addition, when a round was intentionally detonated in the feed chute, damage to chuting and surrounding structure was significant.

6. Aircraft Structural Failure (Figure 44) - S_I 11, baseline 13. There were muzzle clamp failures during the tests, however, the failed parts have been redesigned and strengthened which should prevent further failure. In addition, the fact that these failures did not cause significant damage suggests a reduction in damage possibility. The low possibility of failure of the other modes is unchanged. During the tests, several instances of basic structural failure occurred, but they have been redesigned and strengthened.

7. Aircraft Systems Failure (Figure 45) - S_I 10, baseline 16. The index is reduced primarily because there are no pneumatics in the gun system, thus the possibility of failure is removed. There were several electrical systems failures during testing so the possibility of occurrence factor is increased to moderate. However, they caused no real damage so the damage factor is reduced to low. S_F thus remains the same at six.

8. Personnel Error (Figure 46) - S_I 29, baseline 41. The possibility of an unsafe assembly is reduced because there is considerably more experience with the M-61 gun, better procedures and training are in effect, and there were no problems during testing. Possibility of damage due to unsafe system or aircraft operation remain moderate because the F-15 is a high-performance aircraft which could cause an unsafe condition if operated improperly. In addition, discretion is necessary in firing the gun at low speed, low altitude because of the borderline gas condition shown in the test report (Reference 11).

9. Static Voltage (Figure 47) - S_I 6, baseline 6. The low possibility of this occurrence is unchanged. F_O is very low, but F_{DO} is moderate.

10. Radiation (EMP/EMP) (Figure 48) - S_I 6, baseline 6. Unchanged. F_O is very low but F_{DO} is moderate.

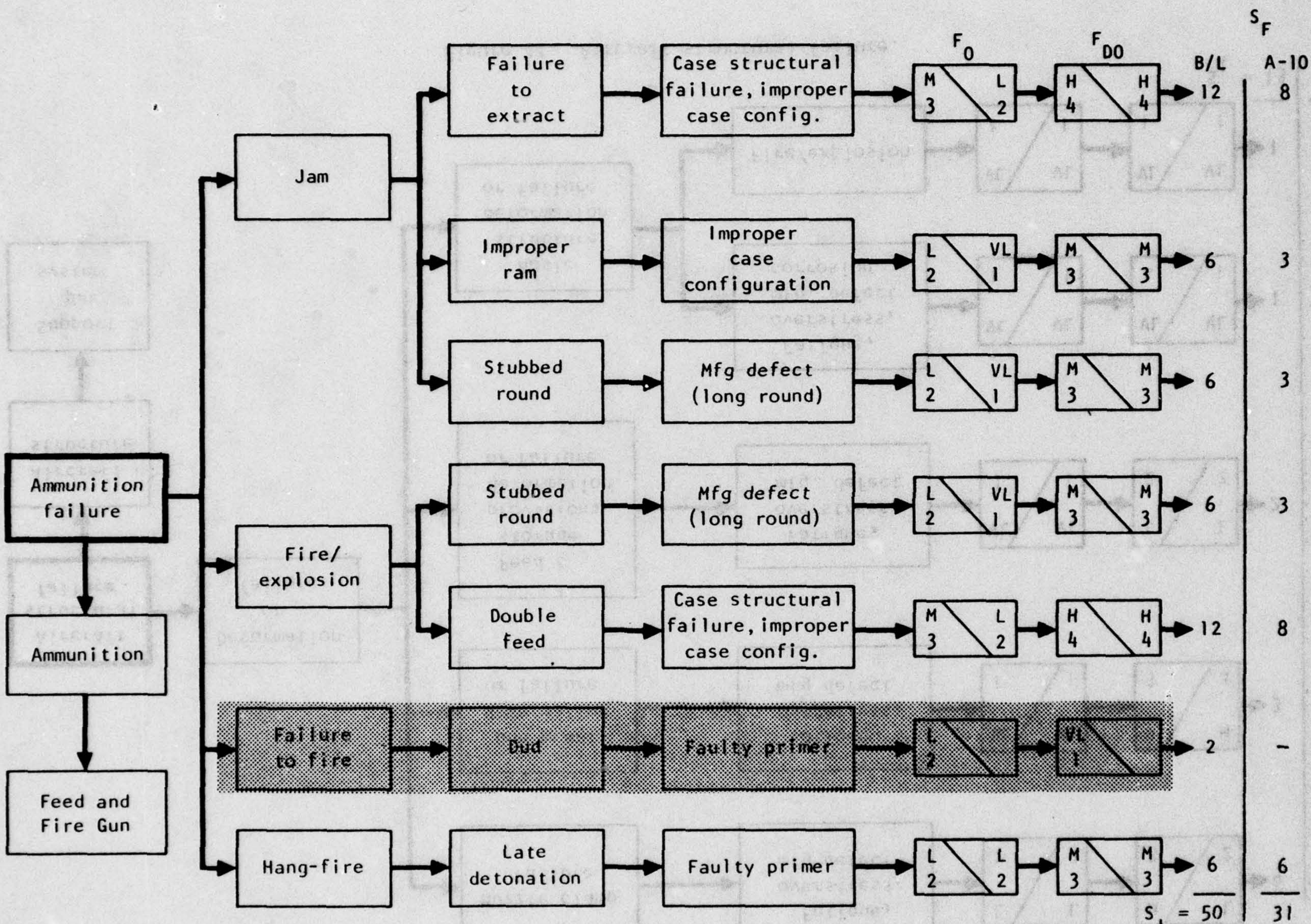


Figure 43. Ammunition Failure

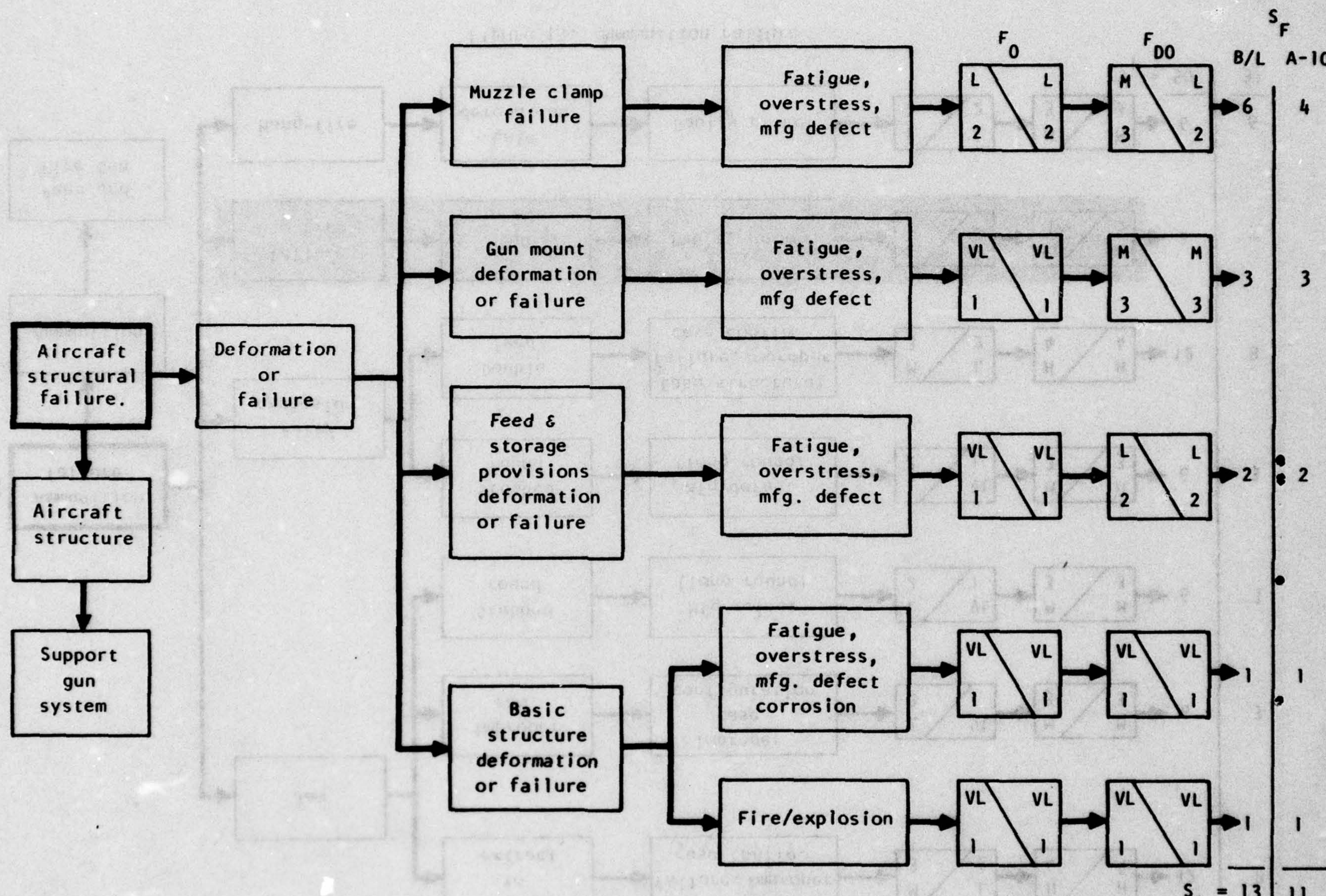


Figure 44. Aircraft structural failure.

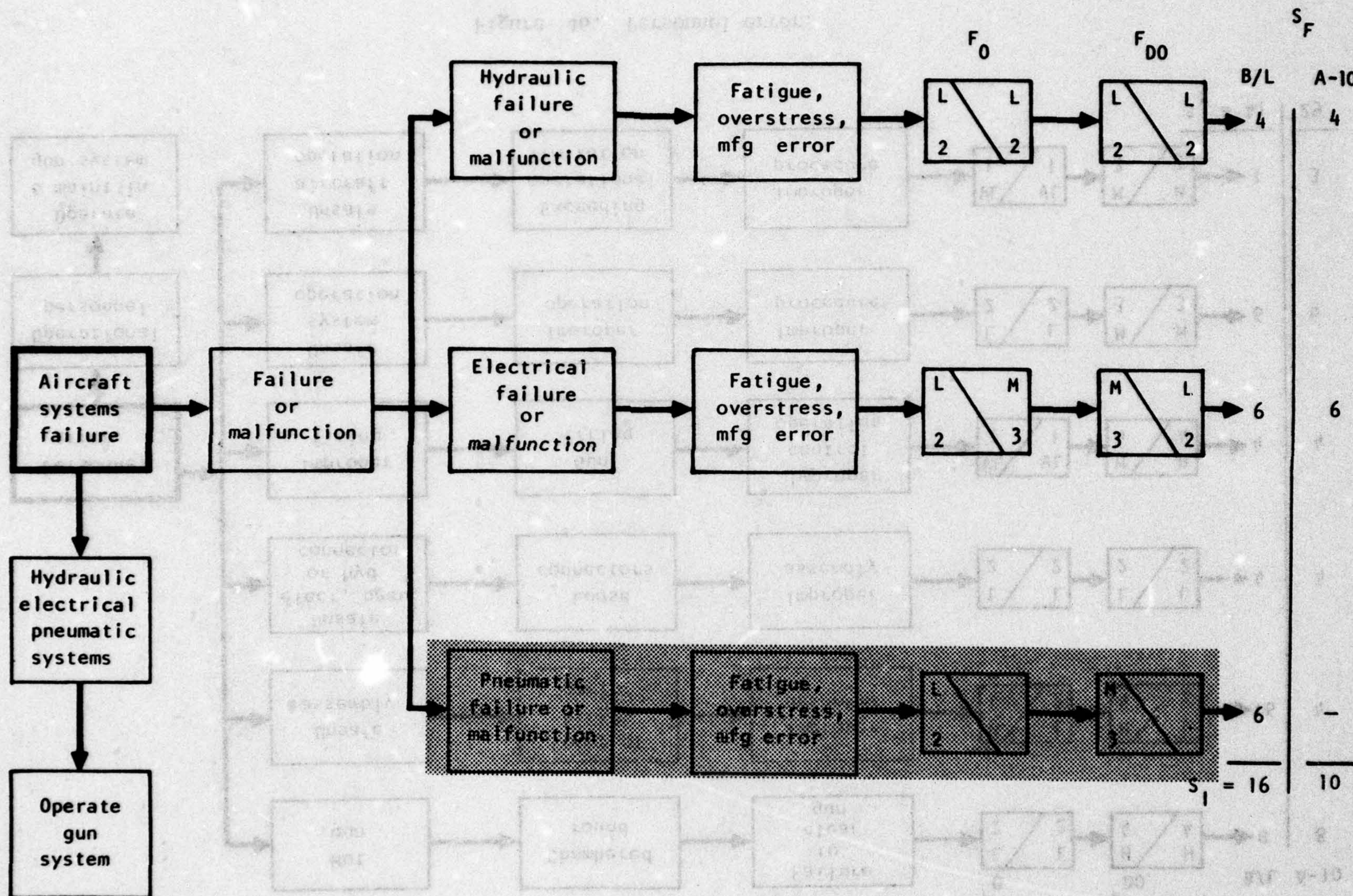


Figure 45. Aircraft systems failure.

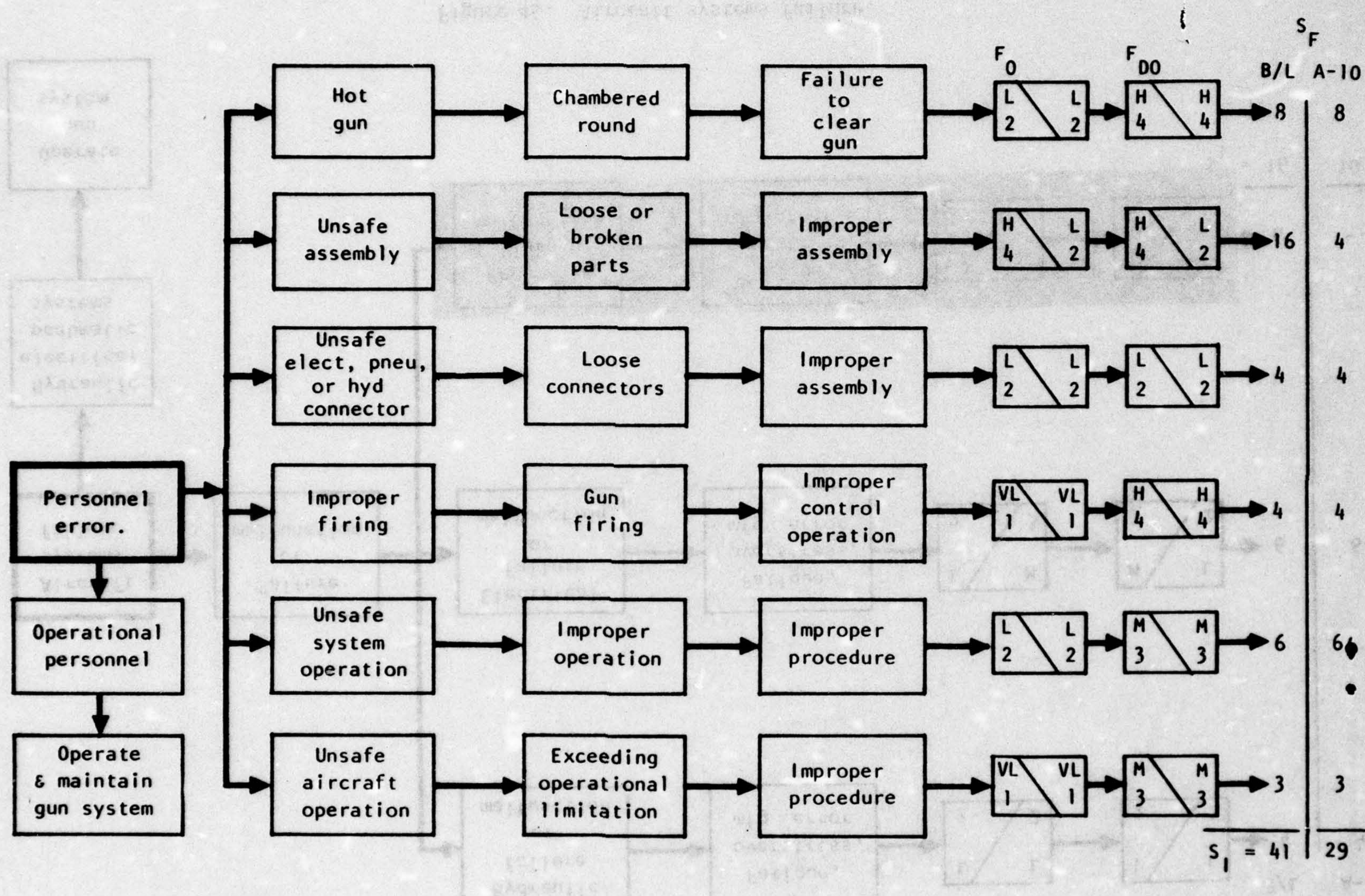


Figure 46. Personnel error.

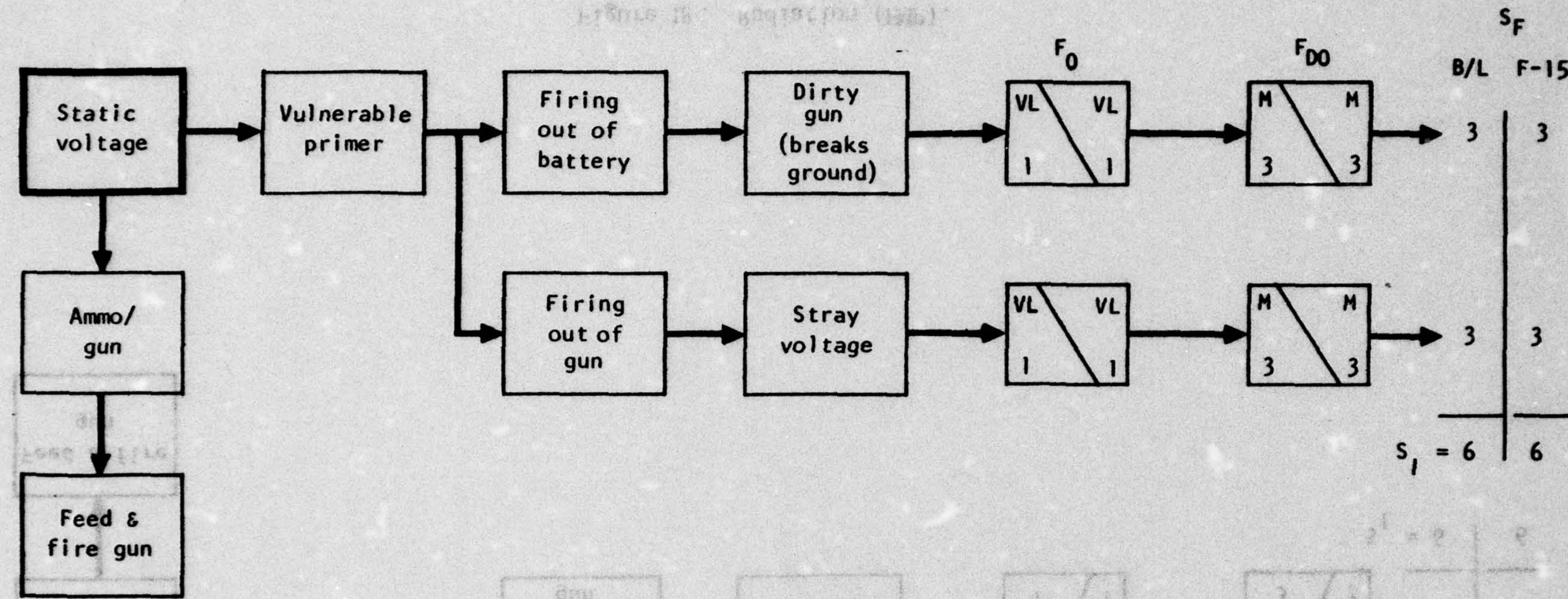


Figure 47. Static voltage.

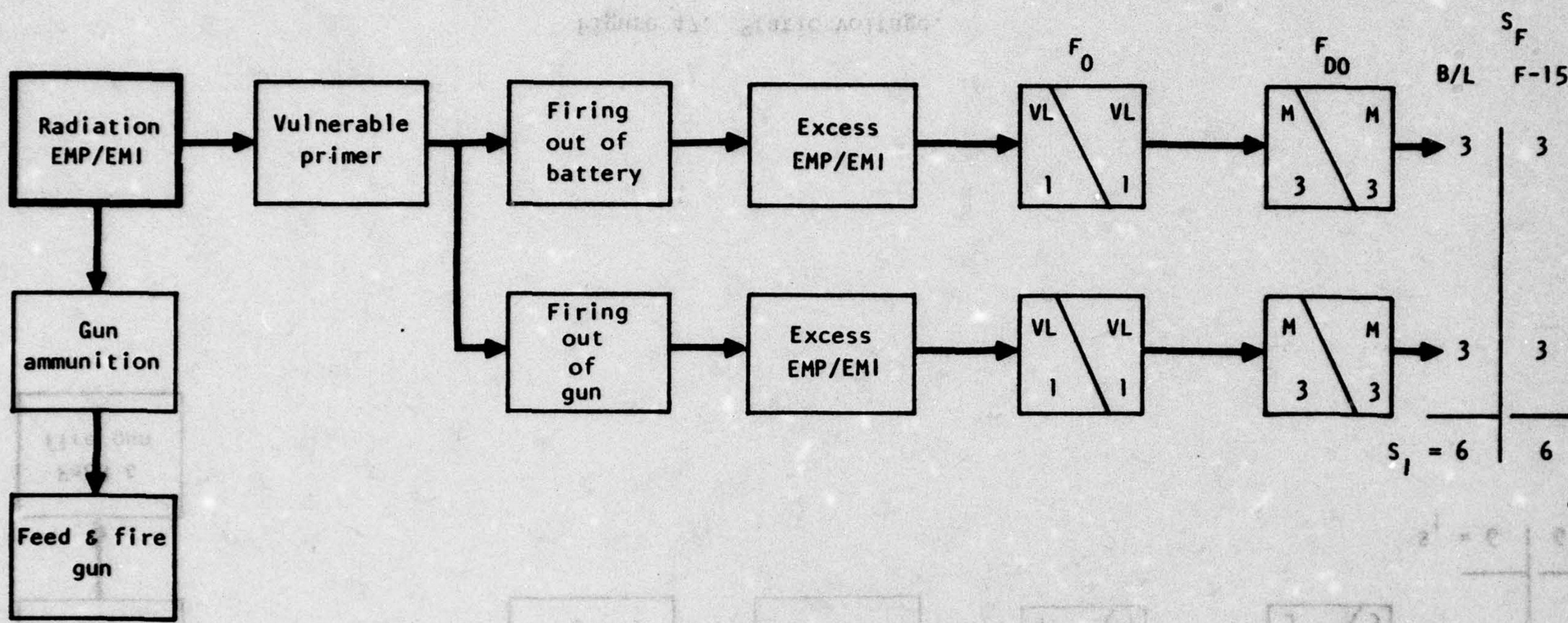


Figure 48. Radiation (EMP).

11. Enemy Fire (Figure 49) - S_I 25, baseline 45. Deletion of the purge system removes this possibility of failure. Further reduction occurs because there is no pneumatic system nor are there fuel lines in the gun compartment.

12. Conclusion - The sum of the S_I, the H_I, is 188 (Table 2), considerably below the baseline index of 315.

CONCLUSIONS

The step-by-step application of the methodology to the A-10 and F-15 aircraft provided statistical results which might be expected. The baseline was prepared from the reported accidents/incidents of operational aircraft while the A-10 and F-15 have the advantage of experience, technological progress, and improved engineering. As shown in Table 2, this advantage is reflected in the 315 S_I for the baseline, 195 S_I for the A-10, and 188 S_I for the F-15.

Large improvements are estimated for the gun. Experience and design changes are expected to reduce the possibility of gun failure considerably, however, double feed (the failure to clear) has caused accidents with the M-61 in the past and the possibility of future incidents cannot be eliminated. The reverse clearing feature of the GAU-8 appears to reduce the liability of cookoff and double feed.

The deletion of the purge system in the A-10 and F-15 of course significantly reduces the H_I. While the number of accidents due to the purge system is statistically small, the potential for catastrophic failure is always present.

Ammunition failure has been very high in the past and the A-10 test data suggests that there may be problems in the GAU-8 ammunition because it is relatively new in service. The S_I for the F-15 was reduced because of the favorable test results, as well as a considered judgment that because of the experience, the ammunition quality would improve.

Large improvements in S_I for enemy fire are accorded the A-10 and F-15 because of the deletion of the purge system, completely in the F-15 and leaving only the structural portion of the ejector in the A-10; also because there are no fuel lines in the gun compartment. The absence of a pneumatic system also aids the F-15 index.

A factor that should be stressed is that the methodology was applied to each aircraft independently and that the S_I summation was not made until both were completely evaluated. The similarity of the numerical values and the reduction of the H_I for both A-10 and F-15 add to the credibility of the approach.

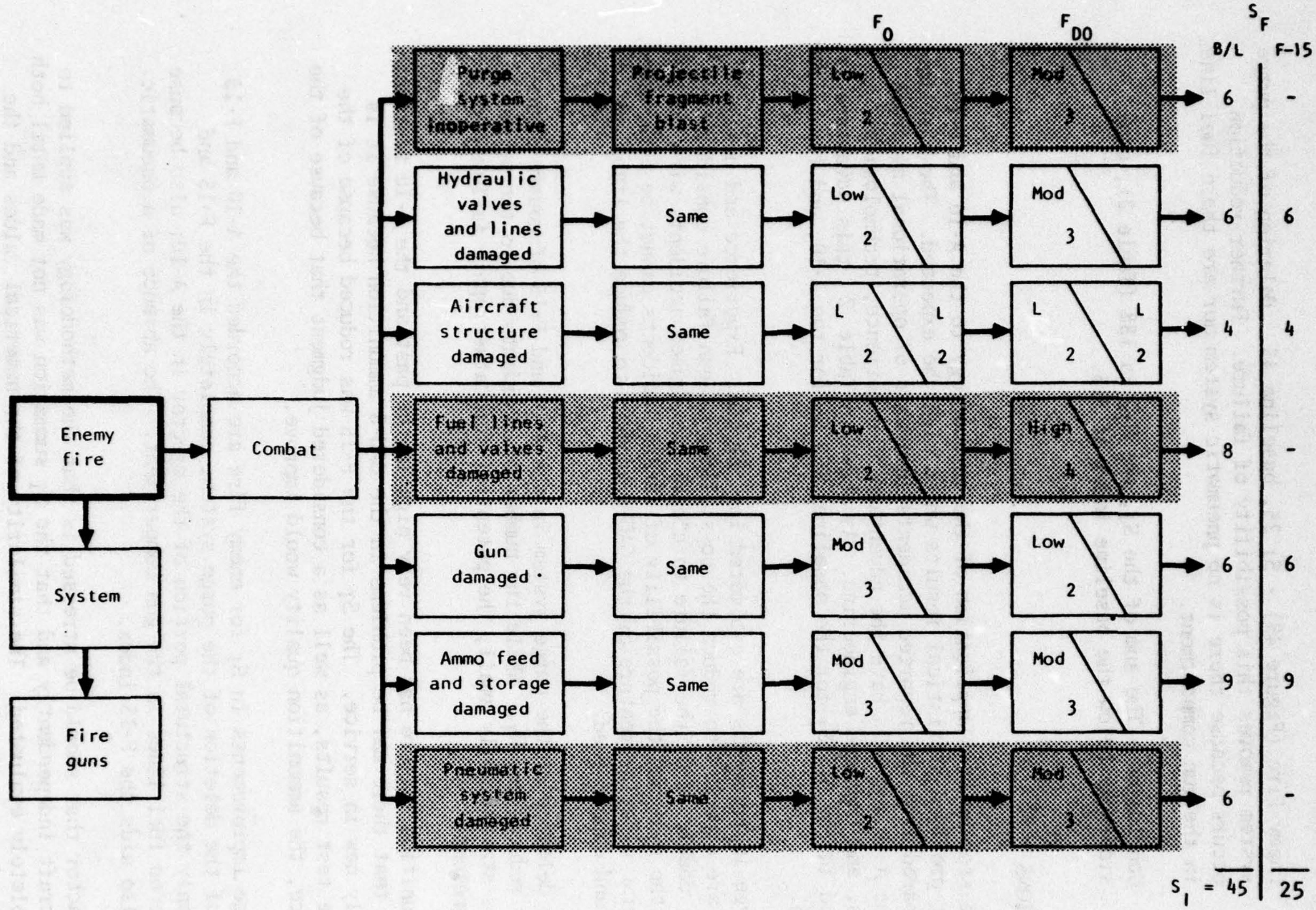


Figure 49. Enemy fire.

TABLE 2. METHODOLOGY APPLICATION

Cause	Severity Index - S_I		
	Baseline	A-10	F-15
Gun failure	56	30	35
Gun drive failure	6	5	6
Feed failure	42	30	29
Purge system failure	34	-	-
Ammunition failure	50	42	31
Aircraft structural failure	13	11	11
Aircraft systems failure	16	14	10
Personnel error	41	24	29
Static voltage	6	6	6
EMP/EMI	6	6	6
Enemy fire	45	27	25
H_I = Hazard index	315	195	188

TASK 2 - TECHNICAL DATA ASSESSMENT

In Task 2, the emphasis shifted from data acquisition to data review, organization, and assessment. The grouping of the accident/incident data into cause and result categories, and the development and application of the methodology materially aided in this task. Because of the large amount of data on hand and the desire to provide a well-organized and easily entered reference set, it was decided to place all reference material in a computer bank.

COMPUTER DATA BANK

Rockwell had developed a data managing computer program that allowed the user to access data contained therein by subject codes, document names, or other identifying pieces of information. The Data Managing Program was originally intended for use in managing large bibliographies. However, it was readily adaptable to handling other forms of data, such as aircraft accident/incident reports.

Each document or accident/incident was coded onto a Bibliography Data Sheet Each sheet had a fixed location for the following 10 items:

1. Index number (AD number, or other index number.)
2. Sponsor I.D. (agency name)
3. Sponsor report number
4. Source/contractor I.D.
5. Source/contractor report number
6. Date (of report)
7. Classification
8. Document title
9. Subject codes (user defined)
10. Comments (user provided)

This format had proven to be very effective in that each document could be summarized for data processing purposes on one page, and that one page could be easily key-punched onto eight standard computer cards. The cards became the permanent record, and could be easily stored or used as needed.

Figure 50 shows an example of the bibliography data sheet used for this program. It has been designed so that key punching of IBM cards may be accomplished directly without requiring transfer of information to computer sheets (green sheets). As shown in the example, the index number is the AD identification provided by the Defense Documentation Center (DDC). For documents that do not have an AD number, a special series of identifiers were assigned for the program. The sponsor identification (ID) is for the Government agency that sponsored development of the document. A standard listing of acronyms is used for this entry. In the example, NATC refers to the Naval Air Test Center at Patuxent River, Maryland. The sponsor report number is WST-113R-74. Since no contractor was involved, the word "NONE" is entered in

Card	Columns 1–11	Columns 12–40 / 41–80
A	INDEX NO.: AD922839L	SPONSOR ID: NATC; SPONSOR REPORT NO.: WST-113R-74
	SOURCE/CONTRACTOR ID: NØNE	SOURCE/CONTRACTOR REPORT NO.: NØNE
2	SAME AS CARD "A"	DATE: SEP74; CLASSIF.: U; FM: M; DOCUMENT TITLE: FINAL REPØRT-NAVY TE
	TITLE (CONTINUED)	CHNICAL EVALVATIØN ØF THE F-14 M61A1 GUN
3	SAME AS CARD "A"	TITLE (CONTINUED): INSTALLATIØN
	TITLE (CONTINUED)	SUBJECT CODES: 0304 1018 3032 4043
4	SAME AS CARD "A"	COMMENTS: RESULTS ØF GRØUND AND FLIGHT
		TESTS ØN F-14 M61A1 GUN SYSTEM FØR FIGHT
5	SAME AS CARD "A"	ER MISSIØN. INADEQUATE GUN GA
		S PURGING SYSTEM LIMITS BURSTS TØ 50 RDS
6	SAME AS CARD "A"	UNTIL A FIX IS MADE TØ PERMI
		T 400 RD BURSTS. FASTENER AND DIVERTER E
7	SAME AS CARD "A"	XIT PØRT PLATE FAILURES WERE
		ALSØ EXPERIENCED DURING TEST PRØGRAM.

FORM AP2090-F-2 NEW 2-77

Figure 50. Bibliography data sheet.

the locations for source/contractor ID and source/contractor report number. The date of the document by month and year is noted. Next, classification and format (FM) of the document is entered. This is used to aid in the rapid retrieval of the document. The document title is next entered, "Final Report, Navy Technical Evaluation of the F-14 M-61A1 Gun Installation." The subject codes for the document are next noted. These allow rapid scanning of the data bank for specific information and listing for use in data analysis tasks. This document is an evaluation; thus, code 03 appears. It is also a final report (code 04). The aircraft systems involved are the gun (code 10) and the purge system (code 18). The primary subjects of the example document are safety (code 30) and ventilation (code 32) problems. The aircraft type involved is a fighter (code 40), and the gun type is the GE M-61A1 (code 43). A section is provided for comments on the content of the document that further aids in selecting priority for review or identification of specific information. In the example, comments show that the gun-gas purging system is inadequate and that a limitation of 50 rounds per burst was recommended by the Navy until a corrective fix is made. Figure 51 shows the format for printout of the data bank material that would have been provided. Listings can be sorted by index number and by specific subject category numbers. This system also provides a means to list a bibliography for the final report with a minimum of clerical effort and cost.

Use on Hazard Study Program

The original intent was to use this data management computer tool to sort, identify, and maintain the over 200 separate documents, and over 400 gun compartment-related accident/incident reports.

```
AD NUMBER       SPNID  SPONSOR REPORT NO.  SR SID  SOURCE RPT NO.  DATE    SC  F
TITLE
SUBJECT CODES
COMMENTS

AD922839L       NATC   W. ST-113R-74       NONE    NONE            SEP 74  U   M
FINAL REPORT - NAVY TECHNICAL EVALUATION OF THE F-14 M61A1 GUN INSTALLATION

RESULTS OF GROUND AND FLIGHT TESTS ON F-14 M61A1 GUN SYSTEM FOR FIGHTER MISSION.
INADEQUATE GUN-GAS PURGING SYSTEM LIMITS BURSTS TO 50 RDS UNTIL A FIX IS MADE
TO PERMIT 400 RD BURSTS.  FASTENER AND DIVERTER EXIT PORT PLATE FAILURES WERE
ALSO EXPERIENCED DURING TEST PROGRAM.
```

Figure 51. Example of data bank information printout format.

Approximately one-half of the documents had been coded when the effort was terminated by mutual agreement between Rockwell and AFAPL. There did not appear to be an immediate need for the data in this form and there was no feasible way to maintain the data files once completed.

GUN-GAS ANALYSIS

Combustion theory and application is a highly complex series of phenomena, the explanation of which is far beyond the scope of this study. Ample literature is available on the subject. However, the influence of combustion on the gun compartment, the gases, materials, and design techniques used to avoid or control dangerous combustion are within scope, along with identification of potential problems with suggested methods of avoiding or alleviating them.

Approach

A knowledge of the composition of gun gases is essential to analyzing the extent of the hazard which is presented by the gas flammability problem. Because the Rocketdyne Division of Rockwell International had a great deal of experience with propellants, they were asked to analyze the combustion characteristics of representative propellant compositions. The selected propellants were Olin Ball Powder (used in the M-50 ammunition which is employed by the M-61 gun), Canadian Industries Limited (CIL) and Rocketdyne RGP 150. The latter two are alternate, advanced propellants which may have future applications. See Figure 52 for an explanation of the terms used.

Eliminating the danger from combustion of gun-gas can be approached in two ways. The first is to purge the compartment to reduce the concentration of the combustible mixture below the flammability limit. Inert diluents, such as carbon dioxide or nitrogen, may be introduced into the compartment but this approach imposes such large weight penalties that it is usually impractical. A simpler, yet effective method, is to supply air in large enough quantities to lower the gas concentration to a safe level. The second approach is to use a suitable method for preventing the gases from damaging the aircraft in case they should ignite. Both approaches were investigated in this study.

For each of the propellants, flammability limits when mixed with air were computed using a standard methodology as described in Bureau of Mines Bulletin 503 (Reference 20). Although the upper flammability limit was noted, the lower limit is of most interest in establishing safety requirements so attention was focused on that mixture.

RGP	Rocketdyne gun propellant
TAGN	Tri-aminoguanidine nitrate
HMX	Cyclo-tetramethylene tetranitramine
NC	Nitrocellulose
DOP	Dioctylphthalate
K_2SO_4	Potassium sulphate
PEG	Polyethylene glycol
HMDI	Hexamethylenediisocyanate
NG	Nitroglycerine
NDPA	Nitrodiphenylamine
DBP	Dibutylphthalate
IRFNA	Inhibited red fuming nitric acid
RDX	Cyclonite
PETN	Pentaerythritol tetranitrate
COMP B	Cyclotol

Figure 52. Propellant terms.

The quantity of air required to keep average composition in a gun bay from exceeding 100 percent of the lower flammability limit during steady-state firing of an M-61A gun at a nominal rate was computed.

The effect of altitude (low pressure) on flammability limits and pressure rise due to combustion was surveyed. Experience with gun installation in fighter aircraft such as F-86, F-100, F-14, F-15, F-105, and A-10 was surveyed and evaluated to establish design criteria.

Gas Composition

Before a complete analysis of the hazards associated with gun-gases could be made, it was first necessary to determine the combustion characteristics of gun-gas/air mixtures. Free-energy thermochemical calculations were made for three different propellant combinations, allowing the gun chamber gases to expand from a normal chamber pressure of 50,000 psia to atmospheric pressure and lower. The three compositions which were evaluated are:

- Rocketdyne, RGP 150: 45.0 TAGN/29.5 HMX/20.0 NC (12.6N)/4.8 DOP/ 0.5 K_2SO_4/0.2 Resorcinol/2.5 PEG-400/2.5 HMDI.

- Canadian Industries Limited (CIL): 64.62 NC (13.4N)/29.38 NC (12.6N)/ 6.0 Ethyl Centralite

- Olin Ball Powder: 50.72 NC (14.4N)/31.08 NC (11.1N)/ 10.0 NG/1.0 NDPA/ 7.2 DBP.

A set of computed data, assuming that the changes in equilibrium composition between 50,000 psia to 14.7 psia occur primarily from the reactions:

$$10\ CO + 2H_2 + 4H_2O \rightleftharpoons 7\ CO_2 + 3\ CH_4 \quad \text{(Olin \& CIL)}$$

$$19\ CO + 13H_2 + 3H_2O \rightleftharpoons 11\ CO_2 + 8\ CH_4 \quad \text{(RGP 150)},$$

are presented in Table 3 for a range of pressures from 50,000 to 0.1 psia. Corresponding equilibrium temperatures are also shown. The total amount of combustible gas thus decreases as the equilibrium shifts with lower pressures and temperatures.

Expansion and cooling of the gas, however, do not follow the thermodynamic equilibrium predictions because of considerations caused by chemical kinetics. The predominant reaction taking place during the expansion and cooling process is the water gas reaction

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \ . \tag{1}$$

A series of calculations was made, using equilibrium constant data available in the JANNAF thermochemical handbooks, to establish the concentrations of the water-gas reactants (CO, H_2O, CO_2, and H_2) at various temperatures, from gun-propellant combustion temperature 2,300° to 300°K. These results, based on equation 2 and plotted in Figures 53, 54, and 55 indicate that there would be a significant shift in gas composition between the high- and low-temperature regions.

$$K = \frac{(CO_2 + x)\ (H_2 + x)}{(CO - x)\ (H_2O - x)} \tag{2}$$

where

K = equilibrium constant

$(CO_2 + x)$ = mole fraction of CO_2 etc

x = fraction disassociated

TABLE 3. GUN-GAS COMPOSITION DATA

	Gas Pressure (psia)							
	50K	27.8K	25K	10K	1K	14.7	5	0.1
Propellant - RGP-150								
Gas Temp (° K)	2,024	1,817	1,783	1,534	1,136	752	674	368
ε	0	1.00	1.01	1.45	7.08	223.30	554.50	13,246.03
Gas composition - mole percent								
H_2	26.3	25.8	25.7	24.5	20.5	12.8	9.9	0.1
H_2O	14.5	14.5	14.5	14.6	14.3	13.4	14.3	19.7
CH_4	1.5	2.0	2.1	3.2	7.1	14.6	16.3	20.2
CO	26.5	25.8	25.6	23.8	17.0	3.3	1.3	0
CO_2	3.2	3.8	3.9	5.2	10.5	21.2	22.6	22.3
N_2	27.4	27.6	27.7	28.3	30.4	34.4	35.4	37.5
Misc	.6	.5	.5	.4	.2	.3	.2	.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Comb gases	54.3	53.6	53.4	51.5	44.6	30.7	27.5	20.3
Propellant - CIL								
Gas Temp (° K)	2,264	2,017	1,976	1,664	1,198	824	763	587
ε	0	1.00	1.01	1.44	6.96	227.11	579.49	18,500.31
Gas composition - mole percent								
H_2	16.7	17.2	17.3	18.1	17.4	13.3	12.0	6.2
H_2O	16.6	16.0	15.9	14.7	11.6	6.0	4.8	1.7
CH_4	.1	.2	.2	.6	3.4	10.8	12.7	19.3
CO	47.0	46.3	46.1	44.5	37.5	21.6	17.8	5.5
CO_2	8.6	9.4	9.5	11.2	18.5	35.2	39.2	52.2
N_2	10.8	10.8	10.8	10.9	11.5	13.1	13.5	15.0
Misc	.2	.1	.2	0	.1	0	0	.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Comb gases	63.8	63.7	63.6	63.2	58.3	45.7	42.5	31.0
Propellant - Olin								
Gas Temp (° K)	2,241	1,999	1,958	1,652	1,194	822	761	582
ε	0	1.00	1.01	1.45	6.98	228.19	582.19	18,501.32
Gas composition - mole percent								
H_2	17.0	17.5	17.6	18.4	17.8	14.0	12.7	7.2
H_2O	17.6	16.9	16.8	15.6	12.5	6.8	5.5	2.7
CH_4	.2	.2	.3	.6	3.5	10.8	12.7	19.2
CO	45.8	45.1	45.0	43.3	36.1	19.9	16.0	3.8
CO_2	8.9	9.6	9.8	11.5	19.0	35.8	39.9	52.7
N_2	10.4	10.4	10.4	10.5	11.1	12.7	13.0	14.4
Misc	.1	.3	.1	.1	0	0	.2	0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Comb gases	63.0	62.8	62.9	62.3	57.4	44.7	41.4	30.2

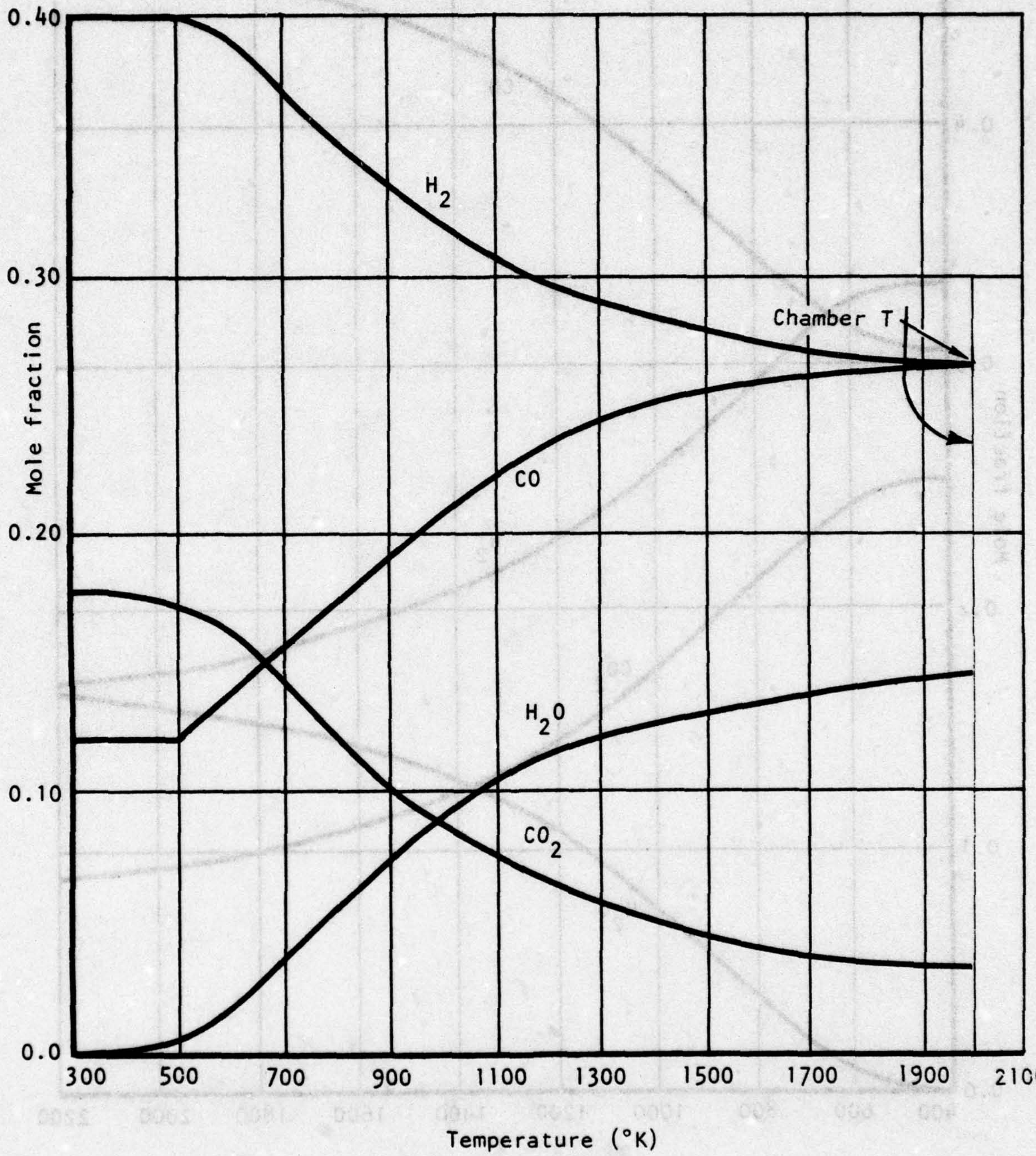


Figure 53. Gas composition of RGP-150.

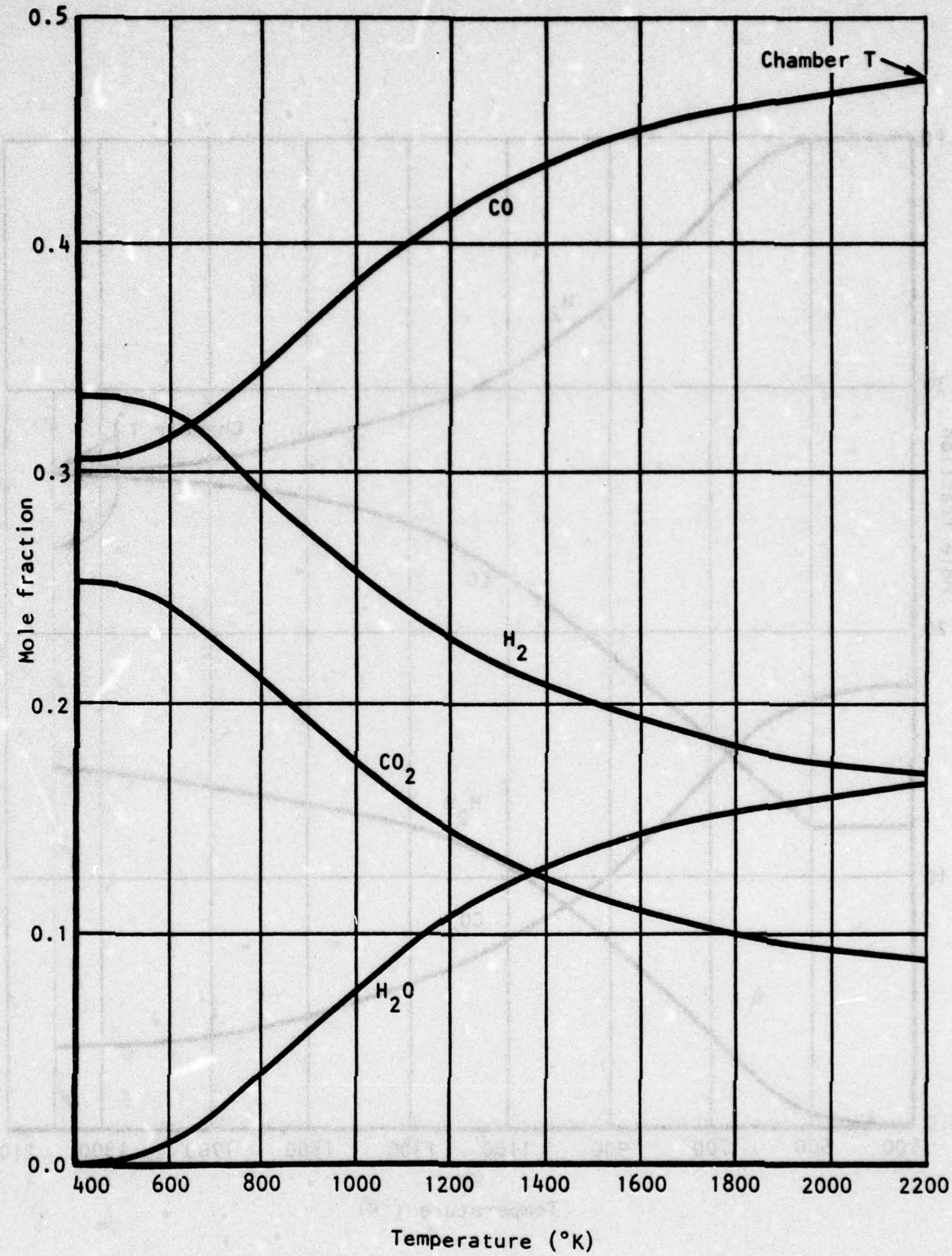


Figure 54. Gas composition of CIL propellant.

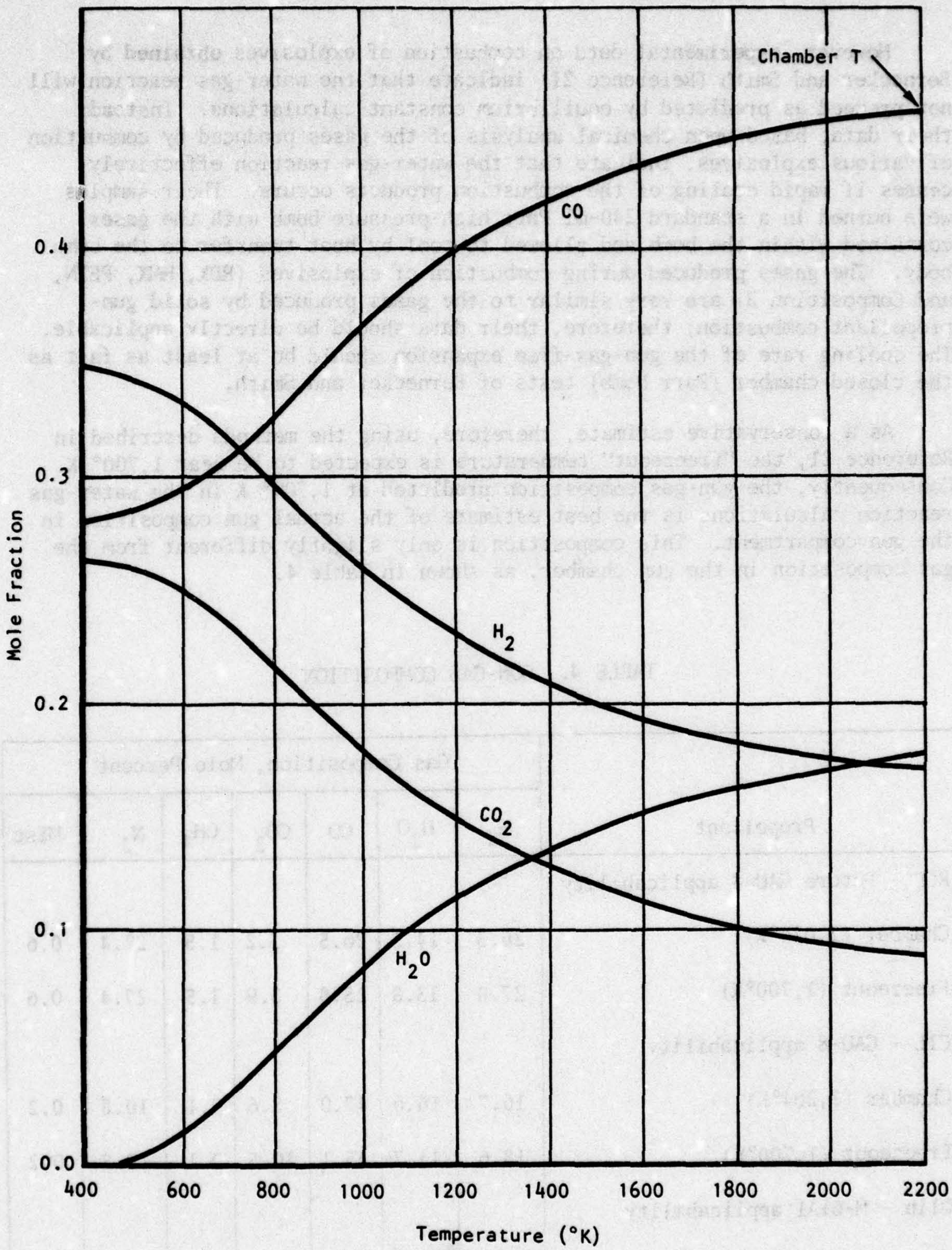


Figure 55. Gas Composition of OLIN Propellant.

However, experimental data on combustion of explosives obtained by Bernecker and Smith (Reference 21) indicate that the water-gas reaction will not proceed as predicted by equilibrium constant calculations. Instead, their data, based upon chemical analysis of the gases produced by combustion of various explosives, indicate that the water-gas reaction effectively ceases if rapid cooling of the combustion products occurs. Their samples were burned in a standard 240-ml Parr high-pressure bomb with the gases contained within the bomb and allowed to cool by heat transfer to the bomb body. The gases produced during combustion of explosives (RDX, HMX, PETN, and Composition B) are very similar to the gases produced by solid gun-propellant combustion; therefore, their data should be directly applicable. The cooling rate of the gun-gas-free expansion should be at least as fast as the closed chamber (Parr bomb) tests of Bernecker and Smith.

As a conservative estimate, therefore, using the methods described in Reference 21, the "freezeout" temperature is expected to be near 1,700° K. Consequently, the gun-gas composition predicted at 1,700° K in the water-gas reaction calculations is the best estimate of the actual gun composition in the gun compartment. This composition is only slightly different from the gas composition in the gun chamber, as shown in Table 4.

TABLE 4. GUN-GAS COMPOSITION

Propellant	Gas Composition, Mole Percent						
	H_2	H_2O	CO	CO_2	CH_4	N_2	Misc
RGP - Future GAU-8 applicability							
Chamber (2,024°K)	26.3	14.5	26.5	3.2	1.5	27.4	0.6
Freezeout (1,700°K)	27.0	13.8	25.8	3.9	1.5	27.4	0.6
CIL - GAU-8 applicability							
Chamber (2,264°K)	16.7	16.6	47.0	8.6	0.1	10.8	0.2
Freezeout (1,700°K)	18.6	14.7	45.1	10.5	0.1	10.8	0.2
Olin - M-61A1 applicability							
Chamber (2,241°K)	17.0	17.6	45.8	8.9	0.2	10.4	0.1
Freezeout (1,700°K)	18.9	15.7	43.9	10.8	0.2	10.4	0.1

Flammability Limits

Any combustible gas or vapor when mixed in the proper proportion with air is capable of producing combustion on being ignited. If small increments of combustible gas are successively mixed with air, a composition will be reached at which the mixture just becomes combustible. The concentration of combustible gas at this composition is referred to as the lower flammability limit (LFL) and represents the minimum concentration of the particular combustible gas or vapor in mixture with air that will propagate flame if ignited. If the concentration of combustible in this mixture is progressively increased, a composition will be reached at which the mixture again becomes noncombustible. The concentration of combustible in the mixture just before this point is reached is known as the upper flammability limit (UFL) and represents the maximum concentration of the particular combustible gas or vapor in mixture with air, that will propagate flame if ignited. All compositions between the upper and lower limits are within "the flammable range" and are flammable. All compositions of mixtures containing less combustible than the lower flammability limit concentration and more than the upper limit concentration are nonflammable by themselves.

As will be shown later, inert gases such as carbon dioxide and nitrogen, have the property not only of depressing or narrowing the flammable range of any combustible gas or vapor, but also of preventing the formation of flammable mixtures when these inert gases are mixed in suitable proportions either with the air, or with the combustible gas, or with a flammable mixture of both. (Reference 22.)

The flammability components of the gases resulting from the combustion of common gun propellants are hydrogen, carbon monoxide, and methane. These gases have flammability limits in air as listed in Table 5.

TABLE 5. LIMITS OF FLAMMABILITY OF GUN-GAS CONSTITUENTS

Gas	Formula	Limits of Flammability*	
		Lower	Upper
Hydrogen	H_2	4.0	74.2
Methane	CH_4	5.0	15.0
Carbon monoxide	CO	12.5	74.2

*Volume % in air at atmospheric conditions

Mixtures of gases may also have flammable limits which are defined by the LeChatelier relationship,

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \text{----} = 1$$

in which N_1, N_2, N_3 etc, are the lower (or upper) limits in air for each combustible gas separately and n_1, n_2, n_3, etc, are the percentages of each of the gases in any lower (or upper) limit mixture in air. While this relationship has been found not to be universally applicable, it gives reasonably accurate results for mixtures of the combustibles in gun gas; i.e., hydrogen, methane, and carbon monoxide.

As an example and using only the three gases of Table 5 and their respective lower limits with the Olin propellant of Table 4:

$$\underset{(H_2)}{\frac{n_1}{4.0}} + \underset{(CH_4)}{\frac{n_2}{5.0}} + \underset{(CO)}{\frac{n_3}{12.5}} = 1$$

and knowing the volume ratio of the three gases to be added to air, say 30.0% H_2, 0.3% CH_4, and 69.7% CO, we find that:

$$n_2 = 0.01\, n_1$$

$$n_3 = 2.32\, n_1$$

We can solve for n_1, n_2, and n_3 and determine that a mixture of

2.29% H_2 (volume)

0.023 CH_4 (volume)

5.30 CO (volume)

92.39 Air (volume)

100.00%

is at the lower flammability limit and that 7.61% (volume) of the three gas mixture in air is at the LFL.

The Bureau of Mines, in one of the earliest investigations of the flammability of mixtures of combustible gases (Reference 23), measured the flammability limits of gases from mine fires, mine explosions, detonation products of explosives, and other gases of similar character; i.e., mixtures of CH_4, CO, and H_2. The test data were then compared with calculated results using the LeChatelier relationship.

Close agreement between the calculated and experimental results for many gases examined validates the use of LeChatelier's relationship for mixtures of the gases.

A more useful formula, derived through a transformation of the basic LeChatelier rule, is, from the foregoing example:

$$L = \frac{100}{\frac{p_{H_2}}{N_{H_2}} + \frac{p_{CH_4}}{N_{CH_4}} + \frac{p_{CO}}{N_{CO}}}$$

$$L = \frac{100}{\frac{30}{4} + \frac{0.3}{5} + \frac{69.7}{12.5}} = 7.61\%$$

in which L is the limit (lower or upper) of a mixture of combustible gases, and p_{H_2}, p_{CH_4}, and p_{CO} are the proportions (volume percent) of hydrogen, methane, and carbon monoxide present in the original mixture, so that:

$$p_{H_2} + p_{CH_4} + p_{CO} = 100$$

or

$$30 + 0.3 + 69.7 = 100\%$$

If the original mixture contains small amounts of air or inert gases (less than 10%), this relationship may be applied without introducing an error of more than 10% in the calculated limits.

When the total volume percent of air and/or inert gases in the original mixture exceeds 10%, the following procedure should be used.

Limits of Original Mixtures Containing Large Amounts of Air and/or Inert Gases

An extension of the law to apply to original mixtures containing large amounts of air and/or inert gases is that, when limit mixtures are mixed, the result is a limit mixture, provided that all constituent mixtures are of the same type; that is, all are lower limit mixtures (lean) or all are upper limit mixtures (rich). The following procedure therefore may be used to calculate the limits of flammability:

Step 1. The composition of the original mixture is first recalculated on an air-free basis; the amount of each gas is expressed as a percentage of the total air-free mixture.

Step 2. A somewhat arbitrary dissection of the air-free mixture is made into simpler mixtures, each of which contains only one flammable gas and part or all of the nitrogen or carbon dioxide.

Step 3. The limits of each mixture thus dissected are read from tables or curves. (See Figure 56.)

Step 4. The limits of the air-free mixture are calculated from the figures for the dissected mixtures obtained in step 3, by means of the equation:

$$L = \frac{100}{\frac{p_1}{N_1} + \frac{p_2}{N_2} + \frac{p_3}{N_3} + \ldots},$$

where p_1, p_2, p_3 . . . are the proportions of the dissected mixtures, in percentages, and N_1, N_2, and N_3 . . . are their respective limits.

Step 5. From the limits of the air-free complex mixture thus obtained, the limits of the original complex mixture are deduced.

The following is an example of the calculation applied to the Olin freezeout composition in Table 4.

H_2	-	18.9%
CO	-	43.9
CH_4	-	0.2
CO_2	-	10.8
H_2O	-	15.7
N_2	-	10.5
		100%

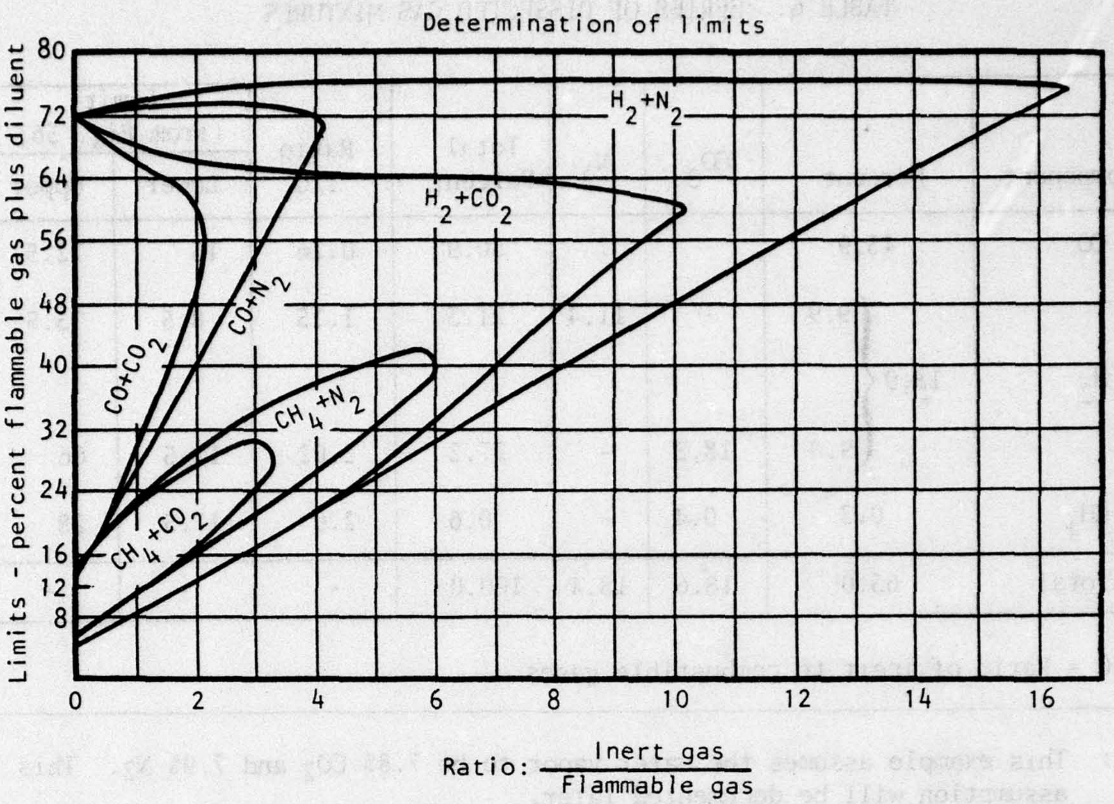


Figure 56. Limits of flammability of hydrogen, carbon monoxide, and methane containing various amounts of carbon dioxide and nitrogen.

1. Since this is already an air-free mixture, Step 1 is omitted and the flammable gases are paired off with the inert gases separately to give a series of dissected mixtures, as shown in Table 6. Some discrimination is needed to choose appropriate quantities, but a fair latitude of choice is usually available.

2. The limits of the dissected mixtures, from Figure 56, are shown in the last two aforementioned columns. For example, the first mixture contains 43.9 percent of carbon monoxide and 7 percent of nitrogen; the ratio between its nitrogen and carbon monoxide is 7/43.9 = 0.16; and the limits from the curve for carbon monoxide - nitrogen mixtures are 13-percent (lower) and 72.5-percent (higher).

TABLE 6. SERIES OF DISSECTED GAS MIXTURES

Component	Percent		CO_2	N_2	Total Percent	Ratio I/C	Limit (from Fig. 56)	
							Lower	Upper
CO	43.9		-	7	50.9	0.16	13	72.5
H_2	18.9	9.9	-	11.4	21.3	1.15	8.5	73.5
		9.0	18.2	-	27.2	2.02	12.5	66
CH_4	0.2		0.4	-	0.6	2.0	17.5	28
Total	63.0		18.6	18.4	100.0	-	-	-

I/C = Ratio of inert to combustible gases

NOTE: This example assumes the water vapor to be 7.8% CO_2 and 7.9% N_2. This assumption will be documented later.

3. The values in the last two columns and in the column "total percent," substituted in the equation, give the two limits of the air-free complex mixture, calculated to 0.5 percent:

$$\text{Lower limit} = \frac{100}{\frac{50.9}{13} + \frac{21.3}{8.5} + \frac{27.2}{12.5} + \frac{0.6}{17.5}} = 11.6\%$$

$$\text{Upper limit} = \frac{100}{\frac{50.9}{72.5} + \frac{21.3}{73.5} + \frac{27.2}{66} + \frac{0.6}{28}} = 70\%$$

Since the original complex mixture did not contain air, the flammability range is therefore 11.6 to 70 volume percent. If, for example, the original mixture had contained air (say 13.4 volume percent), the original mixture lower limit would be:

$$\frac{11.6 \times 100}{(100-13.4)} = 13.39\%$$

The upper limit would be:

$$\frac{70 \times 100}{(100-13.4)} = 80.83\%$$

The chief complication with such calculations is in choosing the appropriate amount of inert gas to pair with each combustible gas. The ratio of inert to flammable gas must not be so high that the mixture falls outside the extreme right of the corresponding curve in Figure 56.

In addition to the gases for which data are given, the gas in the example contains water. Little data exist on the effectiveness of water as an inerting substance for a mixture of combustible gases. However, Coward and Gleadall, Reference 24, showed that the effect of water vapor as an inert gas on the explosibility of methane is intermediate between that of CO_2 and of N_2. Assuming that the effect on hydrogen and carbon monoxide would be similar to that on methane, it seems reasonable to divide the water vapor proportionally between the carbon dioxide and nitrogen and increase the quantities of those gases accordingly. Thus, since the amounts of carbon dioxide and nitrogen in the gun-gas are approximately equal (10.8- and 10.5-percent, respectively), the water was divided equally (to the nearest 0.1 percent) and the portions added to the two inert gases. The total adjusted percentages become CO_2, 18.6 percent, and N_2, 18.4 percent. To check the sensitivity of the limit calculations to the distribution of the water, limits were determined for a case in which all the water was added to the CO_2 and for one in which the water was added to the N_2. Results for all cases are compared in Table 7 and the corresponding limits are listed in Table 8.

Following the procedure just described, the lower and upper flammability limits for the three gun-gas compositions shown in Table 7 composition were computed for the freezeout condition. Results are shown in Table 9.

To evaluate the difficulty of maintaining a low gun-gas concentration by purging a gun compartment with air, the amount of air needed to keep the concentration at 100 percent LFL was computed. For Olin propellant, the LFL of a mixture of gun-gas and air is 11.6 percent. That is, a mixture of 11.6-percent gun-gas and 88.4-percent air is a lower limit mixture or 100-percent LFL. The percentage by weight of the constituents of a gaseous mixture may be determined from the molar compositions by multiplying their corresponding molar percentages by the molecular weights to obtain the weights per mole of the mixture, and then dividing by the total of the weights per mole which is the equivalent weight of the mixture. The procedure is summarized in Table 10 for the gun-gas.

Using the same procedure on a mixture of 11.6-percent gun-gas and 88.4-percent air by vol (100-percent LFL), the weight ratios are obtained as shown in Table 11.

TABLE 7. WATER DISTRIBUTION SENSITIVITY

	Component		Percent	CO_2	N_2	Total Percent	Ratio I/C	LFL	UFL
$H_2O\begin{pmatrix}7.8\ CO_2\\7.9\ N_2\end{pmatrix}$	CO		43.9	-	7	50.9	0.16	13	72.5
	H_2	18.9	9.9	-	11.4	21.3	1.15	8.5	74
			9.0	18.2	-	27.2	2.02	12.5	66
	CH_4		0.2	0.4	-	0.6	2.00	17.5	20
	Total		63.0	18.6	18.4	100.0	-	-	-
$H_2O(15.7+CO_2)$	CO		43.9	-	7	50.9	0.16	13	72.5
	H_2	18.9	9.9	-	3.5	13.4	0.35	6	72.5
			9.0	26.1	-	35.1	2.90	16	65.0
	CH_4		0.2	0.4	-	0.6	2.0	17.5	28
	Total		63.0	26.5	10.5	100.0	-	-	-
$H_2O(15.7+N_2)$	CO		43.9	-	7	50.9	0.16	13	72.5
	H_2	18.9	9.9	-	19.2	29.1	1.94	12.5	74.5
			9.0	10.4	-	19.4	1.16	9	68
	CH_4		0.2	0.4	-	0.60	2.0	17.5	28
	Total		63.0	10.8	26.2	100.0	-	-	-

TABLE 8. EFFECT OF WATER VAPOR DISTRIBUTION

Water Vapor Allocation Percent		Flammability Limit Percent	
N_2	CO_2	Lower	Upper
50	50	11.6	70.4
-	100	11.9	69.4
100	-	11.9	71.7

The rate of airflow required to maintain the mixture at a safe composition depends on the rate of gun-gas generation. The chief source of gun-gas to the compartment is from the gun breech, but this rate depends on the type of gun, its installation configuration in the airplane, firing rate, airplane speed, and altitude. Figure 57, which was developed by McDonnell Douglas as part of its F-15 effort, is a family of representative curves showing the gun-gas flow rate from the breech for the M-61A gun mounted in the F-15. The data include the effect of gases which are blown back through the barrel. Thus, at a mach number of 0.9 at sea level, in this gun-airplane combination, 1 pound of gun-gas per second would flow into the gun compartment.

TABLE 9. LIMITS OF FLAMMABILITY OF GUN-GAS MIXTURES

Propellant	Limits of Flammability Percent	
	Lower	Upper
RGP	11.6	67.6
CIL	13.1	70.4
Olin	11.6	70.4

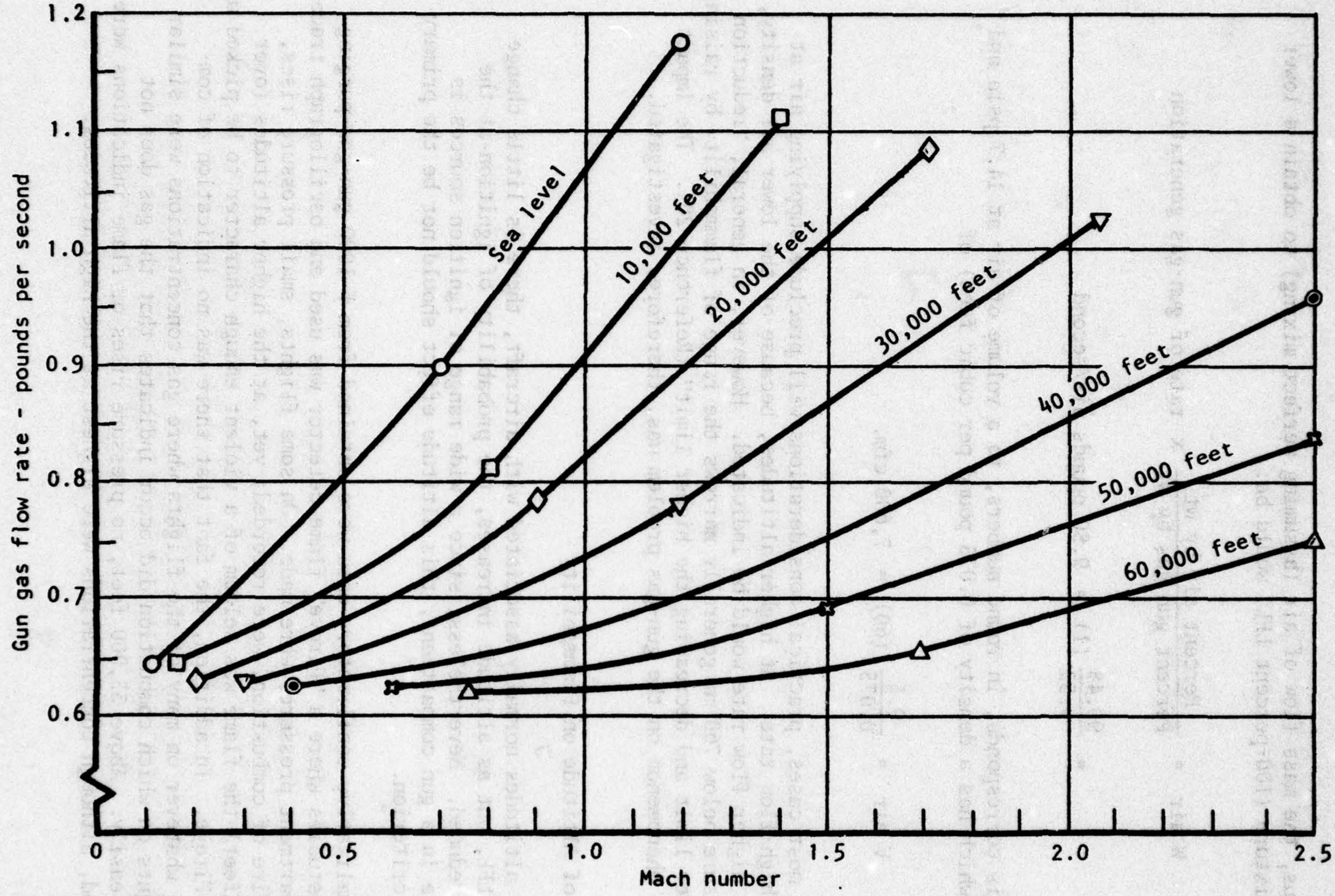
TABLE 10. OLIN GUN-GAS COMPOSITION

Component	Percent by Volume	Pound/Mole	Pound/Mole Mix	Percent by Weight
H_2	18.9	2	0.378	1.62
CO	43.9	28	12.292	52.94
CH_4	0.2	16	0.032	0.14
CO_2	10.8	44	4.752	20.47
H_2O	15.7	18	2.826	12.17
N_2	10.5	28	2.940	12.66
Total	100.00	--	23.220	100.00

Mole weight of mix (gun-gas) = 23.22 pounds per mole.

TABLE 11. 100 PERCENT LFL COMPOSITION

Component	Percent by Volume	Pound/Mole	Pound/Mole Mix	Percent by Weight
Gun-gas	11.6	23.22	2.694	9.52
Air	88.4	28.97	25.609	90.48
Total	100.0	-	28.303	100.00



Courtesy McDonnell Douglas Corp

Figure 57. Total gun gasflow rate (muzzle and breech flow).

Thus, the mass flow of air (assuming perfect mixing) to obtain a lower limit mixture (100-percent LFL) would be:

$$W \text{ air} = \frac{\text{Percent air by wt}}{\text{Percent gun gas by wt}} \times \text{ rate of gun-gas generation}$$

$$= \frac{90.48}{9.52}(1) = 9.50 \text{ pounds air/second}$$

This corresponds, in round numbers, to a volume of air at 14.7 psia and 70° F (which has a density of 0.075 pound per cubic feet) of

$$V \text{ air} = \frac{9.5}{0.075}(60) = 7{,}600 \text{ cfm.}$$

In most cases, practical considerations will preclude supplying air at such a high-flow rate. At higher altitudes, because of the lower air density, an even higher flow rate would be indicated. However, in general, "reduction in pressure below 760 mm generally narrows the range of flammability by raising the lower limit and decreasing the higher limit" (Reference 20). The impact of this phenomenon on the gun-gas problem was, therefore, investigated.

Effect of Altitude on Flammability

At altitudes normally associated with aircraft, there is little change in the LFL, but as altitude increases, the probability of ignition at the LFL is reduced. Nevertheless, since a wide range of ignition sources is possible in a gun compartment, this altitude effect should not be the primary design criterion.

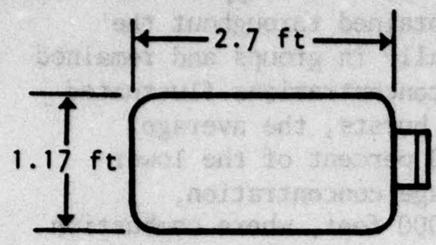
Qualitative confirmatory data were obtained from F-100D gun-gas-purging flight studies where a "Fireye" flame detector was used and oscillograph traces of compartment pressures were made. On some flights, small pressure rises, indicative of combustion, were recorded; yet, at the higher altitudes (over 20,000 feet) the flame was seldom of a violent enough character to be picked up by the Fireye. In addition, the fact that there was no indication of combustion whatever on many of the flights where gas concentrations were similar to flights on which combustion did occur indicates that the gas does not ignite easily. Above 35,000 feet, no pressure rises or flame indications were obtained, although concentrations were highest at the high altitudes.

Recent tests of the M-61A1 gun installation in the YF-17 support the earlier data (Reference 36). Samples of gas were obtained throughout the compartment with bottles which were opened sequentially in groups and remained open for the duration of firing. Although gun-gas concentrations fluctuated over a wide range and showed no consistency between bursts, the average concentrations were below or only slightly above 100 percent of the lower flammability limit. For the maximum indicated average concentration, 116 percent, the airplane was at an altitude of 35,000 feet, where combustion did not take place. There was no record in the test results of combustion occurring.

Theoretical calculations using chemical heats of combustion for constant volume (closed cylinder) burning of the fuels used in References 25 and 26 and of gun-gas were made. The results of such a series of calculations for sea-level initial conditions are:

Fuel	Calculated Pressure (psig)
40 percent hydrogen and air	130
1.15 percent JP4 vapor and air (100 percent sea-level LFL)	117
35 percent gun-gas and air (308 percent sea-level LFL--stoichiometric)	112
5 percent propane and air	107
11.5 percent gun-gas and air (100 percent sea-level LFL)	50

Using these figures as a guide and the experimental data of Reference 26, Figure 58 was prepared to show how constituents and vent ratio (the ratio of the exit area to the volume of the combustion chamber) affect the combustion pressure developed. The estimated curves for gun-gas, of course, are not precise. However, the quantitative error cannot be appreciable since their relationship to the experimental curves must be in the order of the calculated zero vent ratio points and since the limits defined by the experimental curves are rather narrow. The curves show the significant effect of vent ratio in reducing the pressure rise associated with combustion. The stoichiometric gun-gas curve represents the upper limit of possible combustion pressure for gun-gas. Any lesser concentration would be deficient in fuel and any greater would be deficient in oxygen.



Test tanks
- Vol. 3 cu. ft
- L/D = 2.3

Note:

1. Solid symbols denote calculated points using heats of combustion.
2. Open symbols are from experiments of Cousins and Cotten, "Chemical Engineering," August 1951. (Ref 26)
3. Chemical composition of gun gas is 19% H_2, 53% CO, 14% CO_2, and 14% N_2.
4. All percentages are by volume.

(Reference 9)

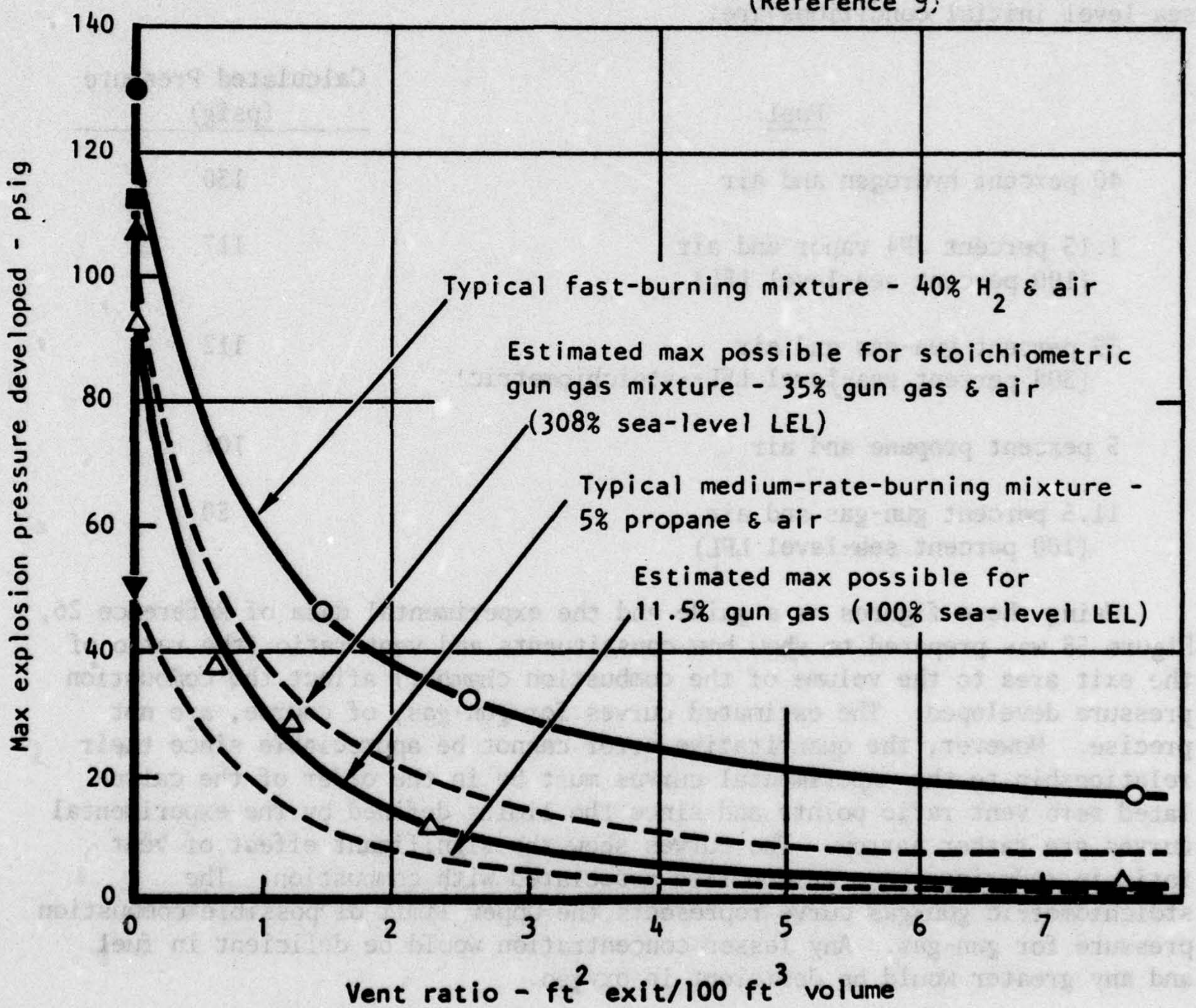


Figure 58. Sea-level explosion pressures.

For a specific fuel-air mixture in a constant volume (zero vent ratio) combustion process, the final pressure attained depends mainly on the initial pressure. In a constant pressure (infinite vent ratio) process, the final pressure is the initial pressure. Therefore, for any vented chamber which falls between these two extremes, the final pressure is also mainly a function of the starting pressure. This reasoning allows the graph of Figure 58 to be converted to the form shown in Figure 59, where the ordinate is combustion-pressure ratio.

At vent ratios greater than 5, the reduction in maximum combustion pressure is negligible. Thus, for a vent ratio of 5 and using the Figure 58 intersections of 100-percent sea-level LFL and for stoichiometric concentrations, the maximum obtainable pressure was determined as a function of altitude. Results are shown in Figure 60. It may be seen that a chamber designed to withstand 2.5 psi bursting pressure would not be damaged by an explosion at sea-level of gun-gas in the 100-percent sea-level LFL concentration and that a chamber designed to 10 psi would withstand an explosion at sea-level of gun-gas in stoichiometric mixture with air. It should be noted further that fuel-rich mixtures (greater than stoichiometric) will produce pressures less than the stoichiometric curve, i.e., the stoichiometric curve represents a maximum limit. The effect of increasing altitude is to greatly reduce the maximum combustion pressure for a given mixture. These predictions were verified during flight tests with F-86 and F-100 airplanes. The gun bays of these airplanes had a vent ratio of about five and had been designed to withstand the pressure (approximately 5 psig) that would result if the purging air inlet scoops were opened in a maximum-velocity dive. From Figure 60 it can be seen that gun-gas combustion pressures cannot exceed 5 psig above 12,000-feet altitude. At 20,000-foot altitude and below, the gases burned as they escaped from the gun breech, and the resulting concentrations in the bay were almost invariably below the lower flammability limit. While this phenomenon called flaming is a property of the particular gun and propellant being considered, in the F-86 and F-100 installations it consistently afforded complete relief from what otherwise might have proved to be a condition requiring more design attention. For this reason, the shaded area marked "flaming" was added to Figure 60 to indicate its effect on the combustion pressure picture.

Considering, then, the area from 20,000 feet up, the data show that destructive pressures cannot result from burning of gun-gases in any concentration. This conclusion is born out by flight-test-measured pressures which have been noted in the figure. The average measured gas concentrations are indicated in percent of sea-level LFL for each point and it can be seen that the test points agree well with the theory as previously developed.

Similar curves for vent ratios of 3 and 4 are also plotted in Figure 60 for comparison.

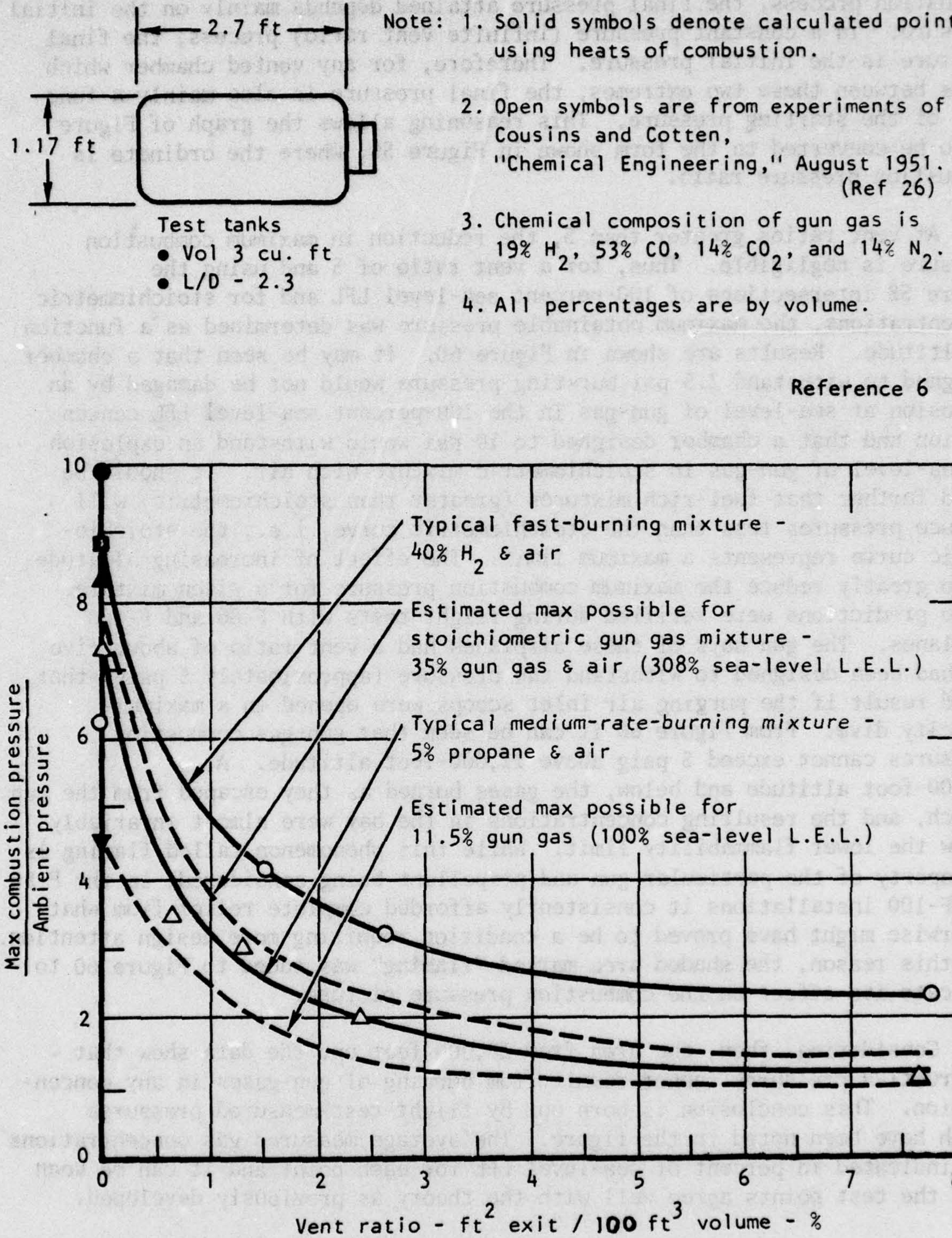


Figure 59. Explosion pressure ratios from sea-level measurements.

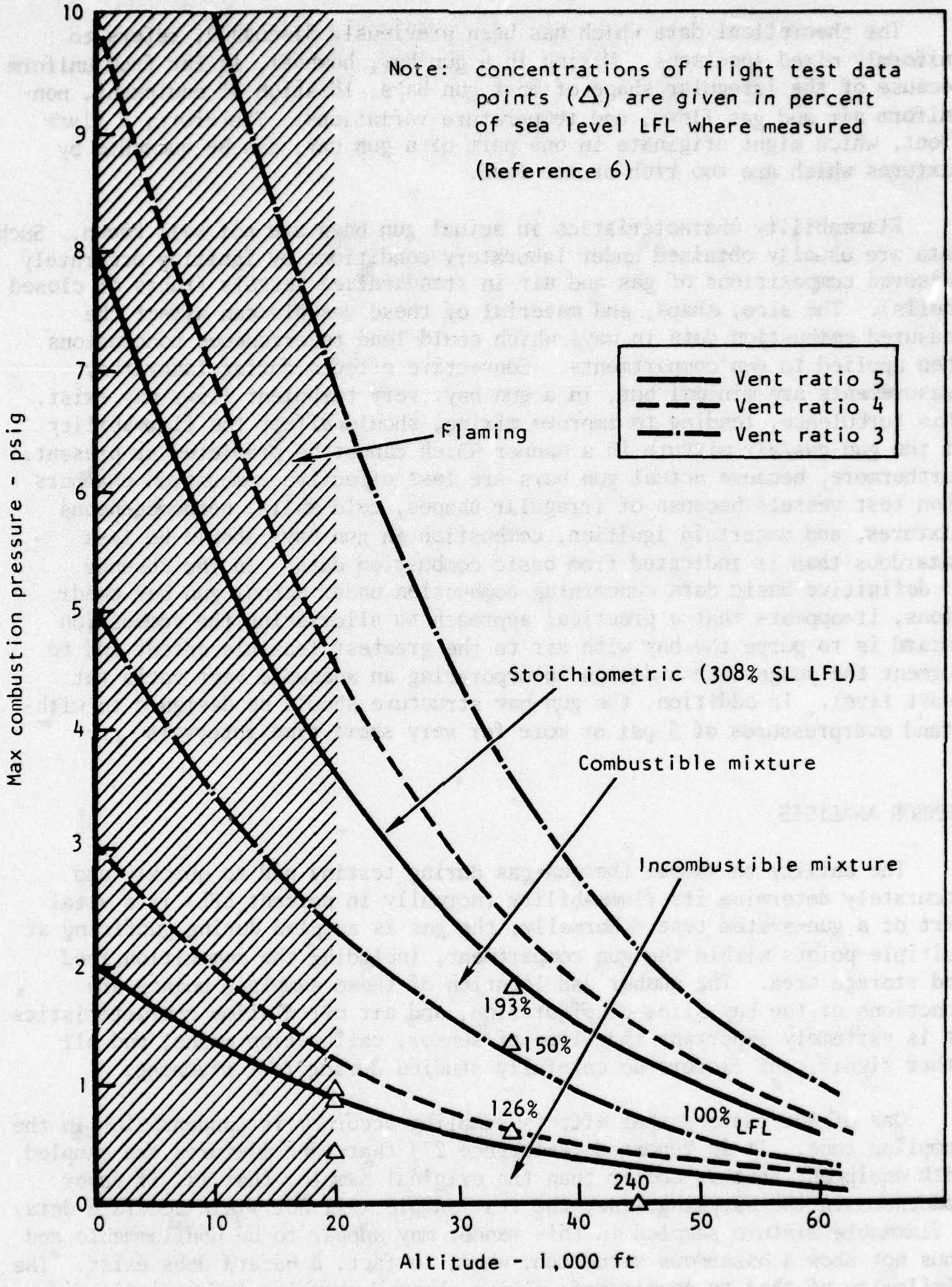


Figure 60. Effect of altitude on combustion pressure for gun gas in a chamber with vent ratios of 3, 4, and 5.

The theoretical data which has been previously discussed, refers to uniformly mixed specimens. Mixing in a gun bay, however, is far from uniform because of the irregular shape of most gun bays, location of equipment, non-uniform air and gas flows, and temperature variations. Therefore, a flame front, which might originate in one part of a gun bay, can be quenched by mixtures which are too rich or too lean.

Flammability characteristics in actual gun bays are not well known. Such data are usually obtained under laboratory conditions by igniting accurately measured compositions of gas and air in standardized vessels (tubes or closed shells). The size, shape, and material of these vessels can affect the measured combustion data in ways which could lead to erroneous conclusions when applied to gun compartments. Convective effects during laboratory measurements are minimal but, in a gun bay, very turbulent flows may exist. This turbulence, tending to improve mixing, should affect the flammability of the gun-gas/air mixture in a manner which cannot be predicted at present. Furthermore, because actual gun bays are less effective combustion chambers than test vessels because of irregular shapes, cold walls, nonhomogeneous mixtures, and uncertain ignition, combustion in gun bays should be less hazardous than is indicated from basic combustion data. In the absence of definitive basic data concerning combustion under actual gun bay conditions, it appears that a practical approach to alleviating the combustion hazard is to purge the bay with air to the greatest feasible extent and to augment the purge with a design incorporating an adequate vent ratio (at least five). In addition, the gun bay structure should be designed to withstand overpressures of 5 psi or more for very short time intervals.

SENSOR ANALYSIS

The ability to sample the gun-gas during testing and to quickly and accurately determine its flammability (normally in percent LFL) is a vital part of a gun-system test. Normally, the gas is sampled during gunfiring at multiple points within the gun compartment, including the ammunition feed and storage area. The number and location of these sampling points are functions of the bay size, configuration, and air circulation characteristics. It is extremely important that type of sensor, calibration means, and all other significant factors be carefully studied during test planning.

One of the factors that affects sampling accuracy is condensation in the sampling tube. It is reported (Reference 27) that when mixtures are sampled with equipment that is cooler than the original sample, that is, if vapor condenses in the sampling line, the test sample will not yield accurate data. A flammable mixture sampled in this manner may appear to be nonflammable and thus not show a hazardous situation, when, in fact, a hazard does exist. The similarity of this to an aircraft flying through changing temperatures and moisture levels cannot be ignored.

Bottle Sampling

Bottle sampling is a technique whereby evacuated bottles are strategically situated to trap the gun-gas by the use of tubing and valves. The sample gas is preserved to be examined at a later time using spectroscopic or other instruments and tests.

The major advantage of this technique is that a specific gas sample can be physically and chemically examined and tested producing very accurate determinations of gas constituents and concentrations.

There are, however, several serious disadvantages.

1. Most gaseous chemical reactions are time-dependent. Thus, if there is a significant interval between the time the gas sample is ingested into the bottle and when it is evaluated, the constituents and/or concentration may have changed depending on the particular chemical reactions involved.

2. The bottles are large and require significant volume to install. In addition, the metering devices, valves, lines, etc, require additional volume for installation.

3. After each use, the bottle must be removed and a new one installed, requiring significant man-hours of effort.

4. The best type of bottle to use is glass, as it causes the least reaction with the test gases. However, glass is very fragile, and therefore requires special handling and usage procedures, also increasing man-hours.

5. Each bottle measures only one sample at one specific time. Multiple samples require multiple bottles (and associated equipment) linked together, or specially controlled by timing and activating devices.

6. The installed bottles must be very clean so as not to induce contamination, and they must be evacuated. To evacuate the bottles, special pumps, valves, and lines are required. To maintain the specified level of cleanliness, special cleaning procedures, and equipment are required.

Catalytic Sensor

The catalytic sensor is a small device that is designed to measure the voltage change across the sensing element as a function of the burning temperature and rate of the combustible gas mixture exposed to the element.

in the presence of a catalyst. These devices can be designed to sense and measure the presence of a specific gas type, such as hydrogen or methane, or a combination of known or unknown combustible gases. They usually can measure the presence of hydrogen faster than hydrocarbon-type gases. Thus, knowledge of the expected gas type or types is important in selecting the appropriate sensor.

The general characteristics and attributes of catalytic sensors are:

1. Immediate (approximately 15-second delays) continuous real-time readout can be obtained using appropriate instrumentation.

2. The sensors are small, lightweight, and do not require excessive support equipment. However, installation constraints such as gun compartment size and location often require special support equipment, such as tubing, lines, pumps, etc.

Even with these attributes, there are some undesirable characteristics, which are:

1. Prior to each use, the sensor and instrumentation must be calibrated by using a specific gas concentration with a known LFL. The calibration gas should be as close as possible in constituents and concentrations as the gun gases to be measured.

2. The specific response time and characteristics are not precisely known. In addition, data indicate that the specific response characteristics vary as the gas constituents vary. Installation constraints and the necessity to use pumping devices, line lengths of up to 20 feet before reaching the sensor, and flowing gas rather than a stationary mixture strains the ability of the sensor to quickly and accurately measure the LFL.

3. These sensors are temperature and pressure dependent. Thus, as the temperature fluctuates, (for example, with altitude changes or long burst lengths), the specific reading also fluctuates even if the gas concentration remains constant. Further, pressure (altitude) effects will result in significant sensor error if a suitable correction factor is not applied. No tests attempting to quantify or correlate the sensor responses to pressure or temperature variations have been found.

4. These sensors are designed primarily for nondynamic environments such as in mines or in oil rigs. There is no catalytic sensor specifically designed and approved for use in an aircraft.

5. It has also been reported that the flame arresters used with many sensors are susceptible to soot clogging and require cleaning, thus increasing maintenance requirements.

6. The catalytic sensor may also be susceptible to catalytic poisoning which results from the burning of the sampled gas and the catalyst during sampling. This can cause response errors.

With these apparent deficiencies known, the obvious approach is to consult the manufacturer for clarification. This was done to the extent possible within the limitations of the study but with disappointing results. These sensors are sold on a generally "as is" basis and the manufacturer is reluctant to provide other than standard instruction manuals. As previously stated, they are primarily intended for ground use and the demand for aircraft use does not justify extensive test and development by the manufacturer. There appears to be ample justification for a qualification test program for catalytic-type sensors.

Spectroscopic Instruments

Special instruments have been developed to utilize physical and optical characteristics of atoms or molecules. The test substance (gases in this case) is excited by (light, heat, electricity, etc), as prescribed by the particular instrument or device, and by observing the resultant characteristics on the metering device, the substance can be identified.

Molecular evaluation is the most accurate method of identifying unknown gases and their respective concentrations.

There are several undesirable aspects, which are:

1. The equipment is usually bulky, delicate, and expensive, thus not suitable for use in aircraft gun compartments.

2. An operator is usually required, but some devices have been developed to operate automatically. The expense, size, and installation problems of these devices are increased accordingly.

3. Installation in an aircraft would pose serious problems, such as: buffeting vibrations, collecting and transmitting a sample to the device, and connecting automatic recording devices.

Ultrasonic Sensor

The ultrasonic sensor, which makes use of the velocity of sound in a medium to measure the percent of gun-gas in a sample, is a new development

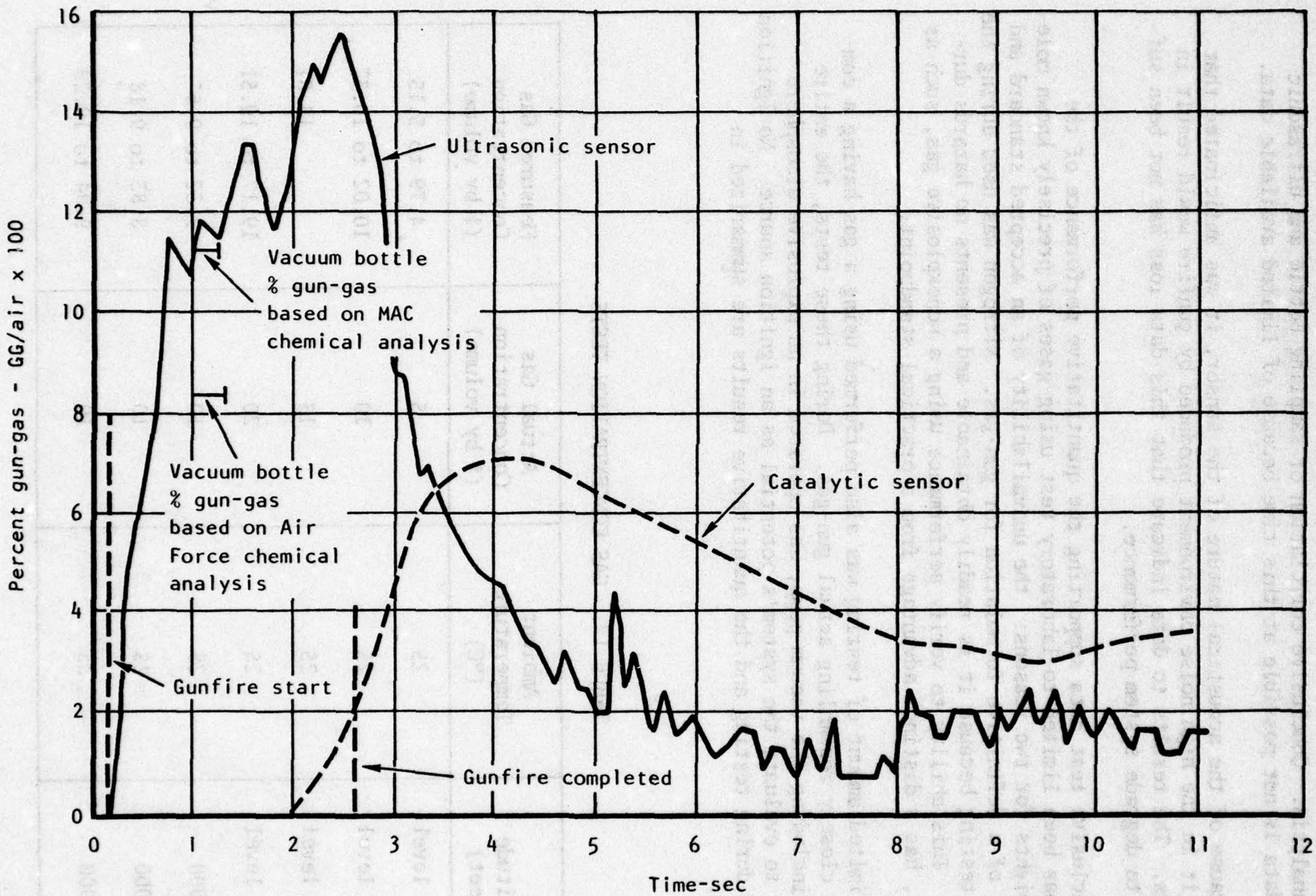
which shows great promise. McDonnell Aircraft Co (McAIR) has done extensive development on this type of sensor, and both ground and flight tests have verified the concept. Portions of their report (Reference 28) on the program follow.

Introduction of gun-gas into ambient air will, in general, result in a change in the propagation velocity of sound due to a change in the molecular weight of the resultant mixture. The ultrasonic gas sensing system measures these changes in propagation velocity and by computation relates them to percent by volume of gun-gas present. The frequency of measurement can be made sufficiently high that the system essentially yields a continuous output. By drawing gas through a sensing cavity the response time becomes that required to exchange the cavity volume, and, in practice, can be made under 1 second. Thus, this system essentially overcomes the limitation of the previously used methods.

Development testing of an ultrasonic system has shown that prediction of gun-gas by volume can be made within ±10 percent of reading if the molecular weight of gun-gas is known. The tests were conducted using a typical formulation for gun-gas and covered an altitude range of 0 to 40 K feet. Ground and airborne testing in an actual gunfire environment were in qualitative agreement with expected results. Quantitative results could not be verified because of the lack of an acceptable standard to which data could be correlated, and because of the lack of an accurate definition of gun-gas constituents. The lack of gun-gas definition can significantly affect quantitative data but does not impair the system in a number of applications, such as purge system evaluation where the ability to depict gas buildup and decay may be of more importance than accurate measurement of peak levels.

A practical installation of the system consists of the sensing unit, vacuum pump, and data system interface. MCAIR has developed two systems utilizing this basic sensing approach. The first uses ground-based computational facilities for data reduction, and the second incorporates a microprocessor as a part of the airborne system. Use of the microprocessor essentially allows the system to operate in real time and with expanded capabilities, such as limit detection and self-monitoring.

Comparisons of the ultrasonic sensor with catalytic sensors and sampling bottles were performed during ground test of the 20mm gun. Figure 61 is representative of this data. The slow response of the catalytic is clearly evident and would be expected to produce large discrepancies in data for a dynamic environment, a fact also clearly evident in the data. Better correlation would, therefore, be expected with sampling bottle data due to their faster response and this was found to be the case. Data between the sampling bottles and ultrasonic sensor showed a reasonable correlation, and discrepancies can be accounted for in terms of chemical analysis inaccuracies, gun-gas constituent uncertainties, and possible bottle leakage due to time lag in performing the



Courtesy of McDonnell Douglas (Ref 28)

Figure 61. Sensor comparison.

actual analysis. Conclusive correlation of sampling bottle and ultrasonic sensor data is not possible at this time because of limited available data.

Because of the acoustical nature of the sensor, it was anticipated that placing it in the high noise environment produced by gunfire would result in data loss. The results to date indicate that this data loss has not been sufficient to degrade system performance.

Conclusive test data supporting the quantitative performance of the sensor has been limited to laboratory test using gases of precisely known molecular weights for two reasons: the unavailability of an accepted standard and the lack of a definitive formulation for gun-gas. Nitrogen was used during the bulk of testing because it is readily obtainable and presents no hazards during use. This ability to verify performance using a nonexplosive gas, such as nitrogen, has a distinct advantage from a practical standpoint.

A limited amount of testing was also performed using a gas having a composition closely resembling actual gun-gas. During these tests, the entire system, including the vacuum pump, was operated in an explosive atmosphere in order to evaluate the system's potential as an ignition source. No ignition occurred during testing and the quantitative results are summarized in Table 12.

TABLE 12. GAS CONCENTRATION TESTS

Altitude (feet)	Ambient Temperature (°C)	Actual Gas Concentration (% by volume)	Measured Gas Concentration (% by volume)
Sea level	25	5	4.79 to 5.15
Sea level	25	10	10.02 to 10.37
Sea level	25	15	14.81
Sea level	25	20	19.17 to 19.51
10,000	25	10	9.32 to 9.67
20,000	25	10	8.83 to 9.18
35,000	25	10	9.94 to 10.29

CONCLUSION

Gas-sensing systems developed using the ultrasonic sensor described in this paper have successfully demonstrated the capability to perform reliably in an airborne environment, providing reasonable qualitative performance. Verification of quantitative performance has been primarily limited to laboratory testing performed under controlled conditions, although a limited amount of data exists that indicates a reasonable correlation with sampling bottle data taken during actual gunfire. The response time of the ultrasonic sensor is significantly higher than previously used catalytic sensors; this is of particular advantage in providing time histories of gun-gas in high fire-rate gun systems. The principle disadvantages of the sensor are the requirement of a precise definition of the molecular weight of gun-gas if reasonably accurate quantitative results are to be obtained, and the requirement that this molecular weight differ significantly from that of ambient air. Satisfying the second requirement has proven to be of no difficulty. The first requirement, however, has proven difficult to satisfy with the precision and confidence necessary to specify system accuracy at the level achieved during laboratory testing. With regard to this requirement, it must be emphasized that an incorrect definition for molecular weight does not impair qualitative data. Therefore, even with no molecular weight information available, the sensor could provide relative data pertaining to the performance of gas-purging systems.

Sensor Comparison

The various types of sensors have different response characteristics. The spectroscopic and ultrasonic are the most accurate real-time sensors. The catalytic sensor has a response delay as well as a temperature/pressure-induced inaccuracy. Both are dependent on the specific gas type and concentration. The bottle sampling technique is accurate (unless chemical process changes occur between sampling and testing the sample), but only one sample time is available per bottle.

Sensor Uses

In recent years, the use of sensors to test the gun-gas composition in aircraft gun compartments has increased. Recent tests utilizing catalytic, bottle, or ultrasonic sensors are: gun firing test programs, including ground and flight tests, for the A-10, F-15, F-4, YF-17, and F-16.

Installation

Often, physical constraints require that the actual sensor be located other than in the gun compartment. When remote sensing is mandatory, pumps and lines are required to transfer the gas samples to the sensors. The

installation requirements such as line sizes, lengths, and pump requirements are determined to suit the individual sensor and aircraft.

A typical remote sensing installation is shown in Figure 62. In this installation, there are three sensor circuits, each with independent lines, pumps, sensor devices, and instrumentation. Each circuit is numbered and color-coded for easy identification.

Pumping lengths can be up to 20-25 feet, and remote instrumentation can be in any convenient location.

Some recent tests use bottle-sensing techniques. An example is the YF-16 prototype aircraft tests.

Figure 63 shows a typical bottle installation.

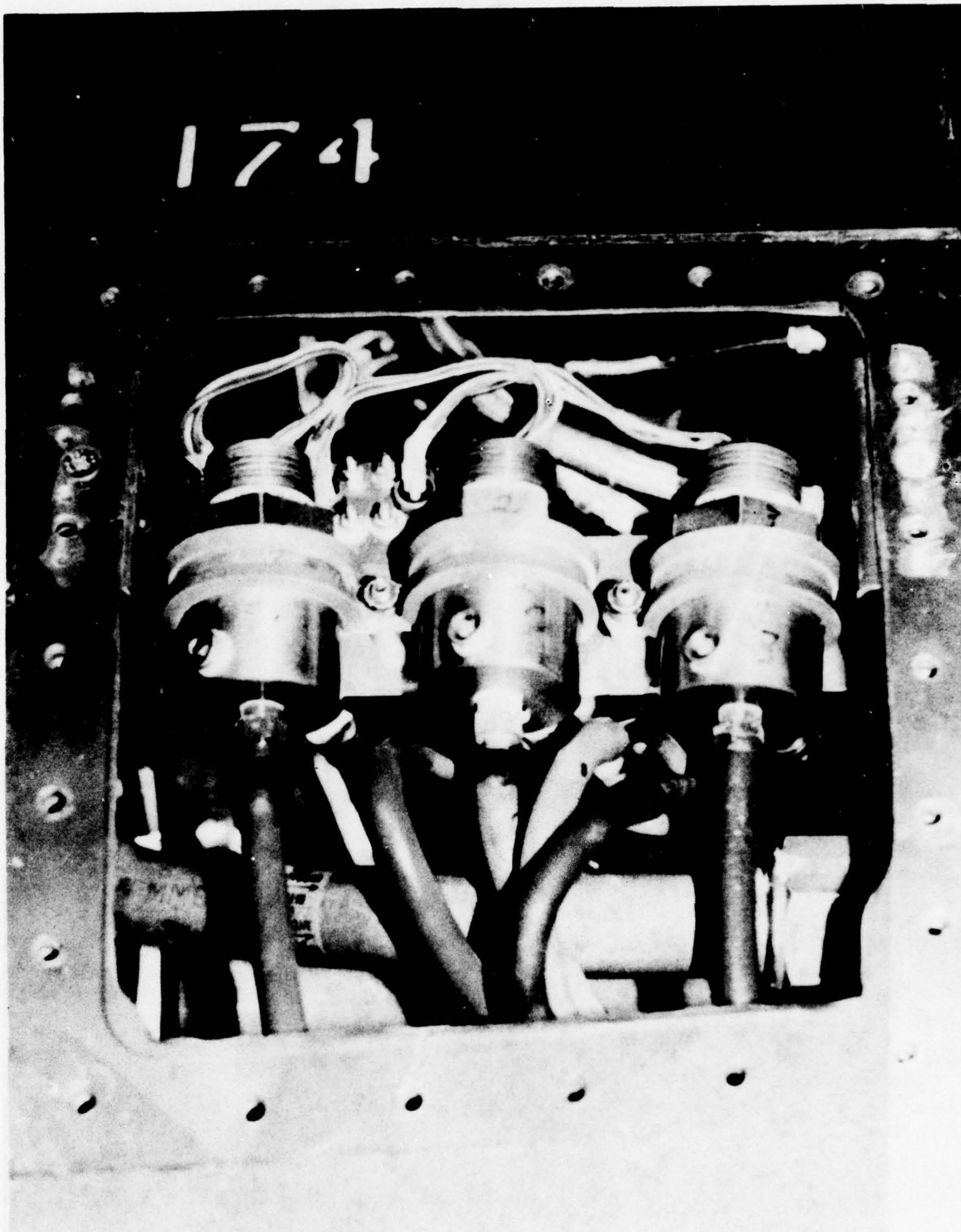
Sensor Analysis (Test Hardware)

As part of this program, Rocketdyne performed an evaluation of catalytic sensors that had been used in prior test programs. The report of this evaluation follows.

Evaluation and analysis of test data were conducted and hardware that was used in the test was examined physically. The effort consisted essentially of two tasks (1) physical examination of catalytic combustion sensors used in the CIC model CCS detection system, and (2) analysis of experimental data reported in ground and flight-test engineering reports.

The hardware used in the tests consisted of a number of catalytic sensors, components of a pumping system, and electronic controls and displays. External examination of the sensors indicated various degrees of use and handling. The purpose of this examination was to determine if the surface of the catalytic elements showed external deposits or other indications of deterioration, which might result in the lowering of performance-induced by catalytic poisoning. Some casings were in fairly clean condition indicating limited use, while the surfaces of others were deteriorated from external deposits, use of wrenches, etc. Five sensors, ranging from the cleanest to the most deteriorated, were selected for detailed examination; these were numbered in increasing order of external deterioration: No. 6, 1, 3, 4, and 10. The condition of sensors No. 6 and 1 indicated very little use, while sensors No. 4 and 10 indicated extensive use.

These five selected sensors were disassembled, the flame arresting shields were removed, and the conditions of reference and detecting sensors were examined under magnification. Each sensor consisted of one hot wire showing a varied degree of oxidation and one hot wire coated with a yellowish substance. The exception was sensor No. 6 (least used). None of its hot



(ADTC Photo)

Figure 62. F-4 catalytic sensor installation.

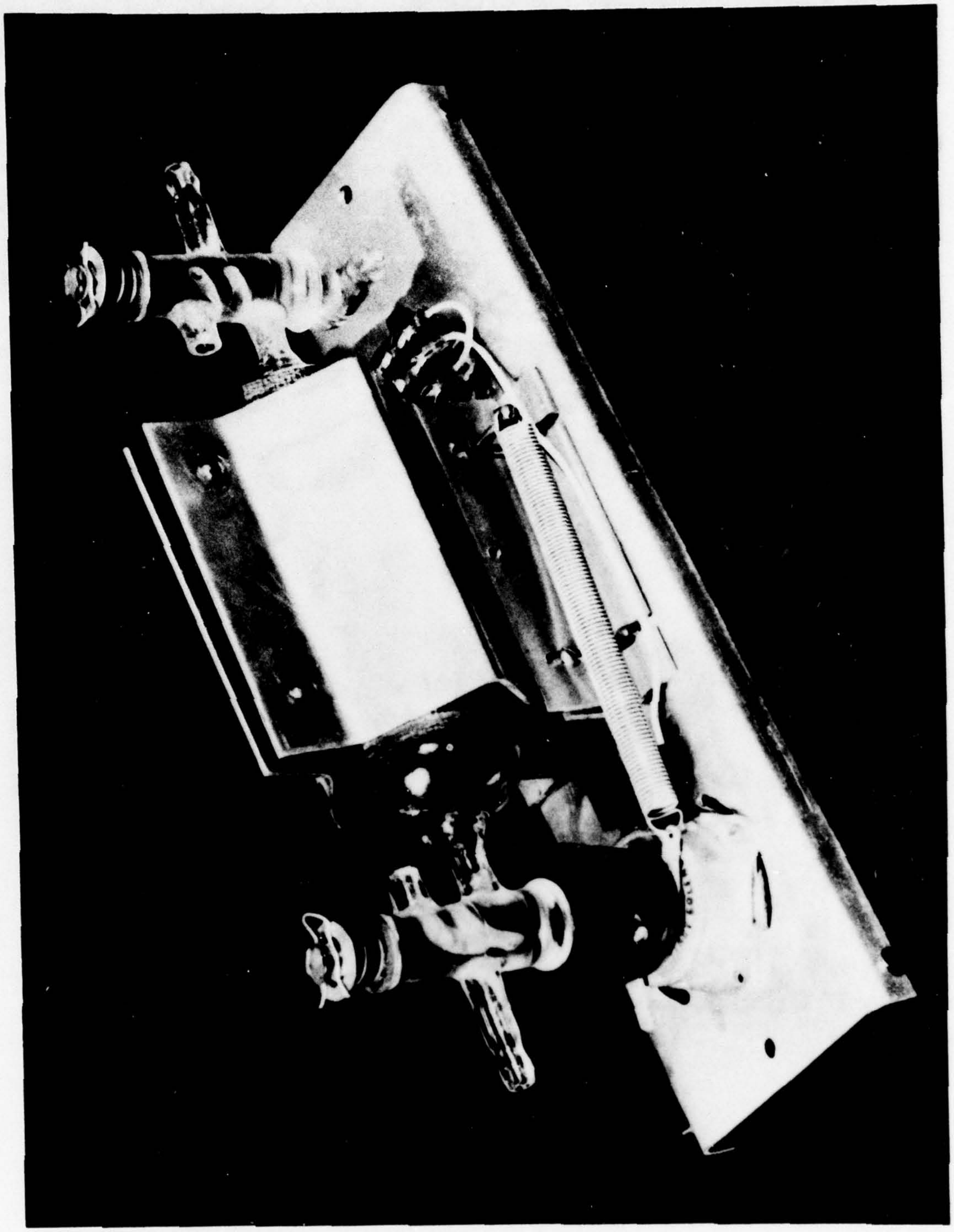


Figure 63. Typical vacuum bottle installation.

wires were coated with a yellowish substance, but one of the wires was lavender in color while the other sensor hot wire appeared to be somehow oxidized. One photograph, Figure 64, is included for reference. The others were not included because the black and white does not show the variation in the wire coatings.

The conditions of the detecting sensors, as measured by the coloring and overall appearance, varied to some extent, and their sensitivity of response and overall performance might have been affected detrimentally as a result of varied degrees of use. Without experimental testing, however, it is not possible to state positively if catalytic poisoning took place. Detailed examination of detection test results was conducted. Catalytic combustion detectors sense presence of flammable gases as a result of temperature increase in the hot wire induced by catalytic combustion. This type of measurement is temperature-dependent, and the instrumentation must be calibrated before the sensors can be used.

According to available information, calibration of the system was carried out on the ground under ambient conditions, while actual testing was performed in both ground and flight-test environments, ranging in temperature from 11° F to over 200° F. Such drastic temperature variations could affect the detector sensitivity and performance. Consequently, available data were examined in order to detect any dependence or relationship between gun compartment temperature and recorded readings for flammable gas concentration expressed as percent of LFL. The gun was operated in low and high firing modes, and different numbers of rounds were fired during various tests. Generally, the temperature of the gun compartment was higher during the high firing mode than during the low firing mode, and highest temperatures were observed when large numbers of rounds were fired. It might be postulated that during such high firing modes with many rounds fired, higher concentrations of flammable gases would be generated in the gun compartment, and that a direct relationship exists between the rate and the number of rounds fired, temperature of gun compartment, and the amount of flammable gases generated. Taking this hypothesis into consideration, available data on firing were examined.

Test information was grouped in three temperature ranges: low (peak 17° F, average 12° F); medium (peak 47° F, average 28° F); and high (peak 142° F, average 57° F), as shown in Table 13. As can be seen from this table, the highest values for combustible gases were obtained in the area of medium temperature range, when an average of 100 rounds were fired for an average period of 2.6 seconds, with a temperature peak of 47° F and an average temperature of 28° F. The LFL in this case was 20 percent, while the average was 12.5 percent. In the high-temperature range, when an average of 152 rounds was fired over a period of 2.37 seconds, the recorded concentration of flammable gases was less than half of one observed in the medium temperature range (percent LFL peak nine, average five). If the assumption made previously on direct relationship between rounds fired, temperature, and flammable gas concentration is correct, then just the

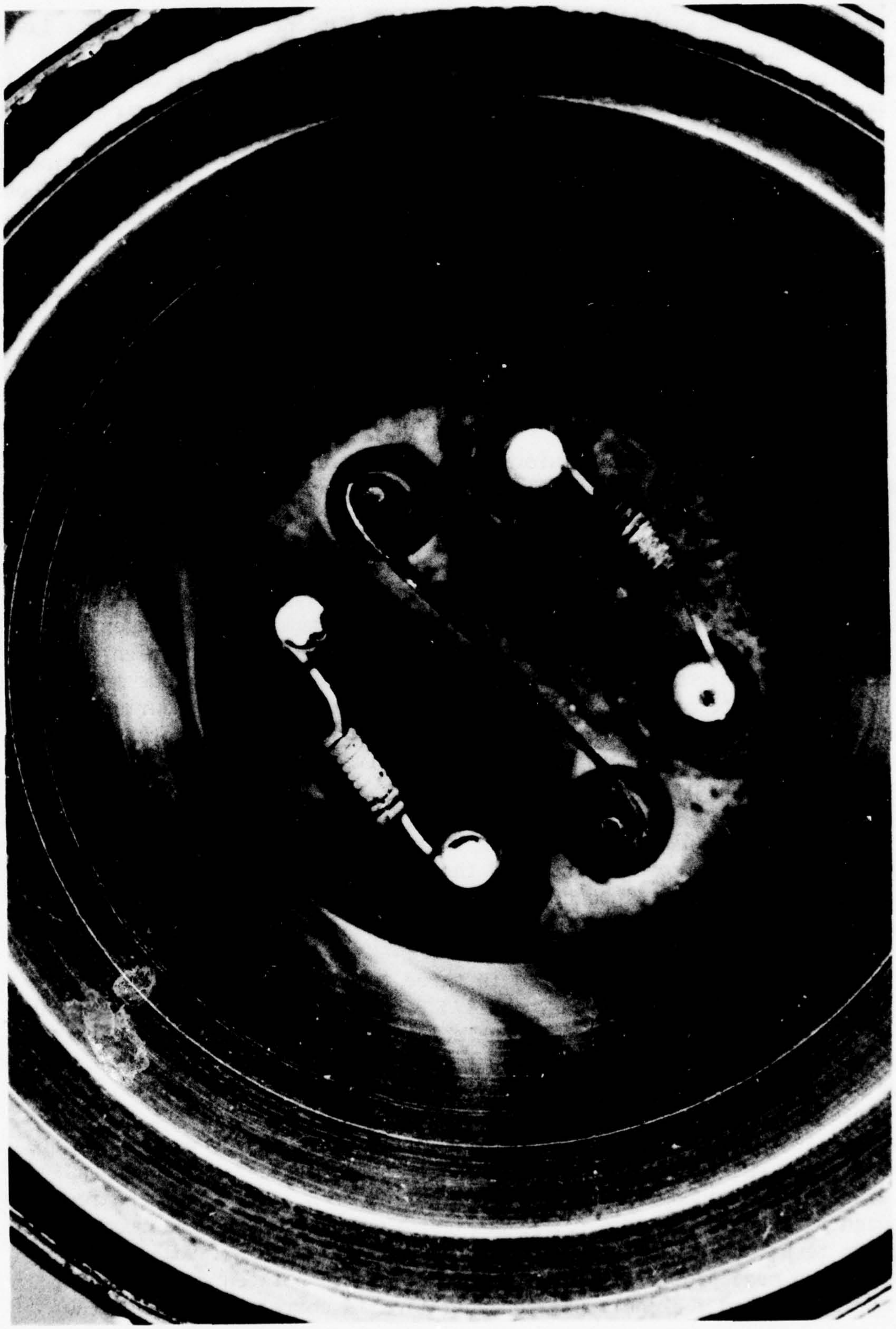


Figure 64. Gun-gas sensor.

TABLE 13. FLIGHT TEST DATA, 30mm GUN

	Temperature (° F)		Fire		Gas Concentration (% LFL)		Flight	Purge No.
	Peak	Avg	Rounds	Time (sec)	Peak	Avg		
Low Temp	14	9	13	0.54	2	1	14F	1
	16	11	37	1.23	2	3		2
	20	16	62	1.93	6	5		3
Low Avg	17	12	37	1.23	4	3		
Med Temp	56	24	100	3.02	10	7	14F	5
	40	22	112	1.79	26	10		6
	42	25	70	2.16	18	13		7
	51	40	120	3.58	29	20		8
Med Avg	47	28	100	2.6	20	12.5		
High Temp	105	42	121	1.93	6	4	19F	1
	189	79	308	4.61	13	6		2
	140	52	108	1.74	5	4		3
	136	44	120	1.91	11	5		4
	142	66	103	1.67	11	5		5
High Avg	142	57	152	2.37	9	5		

opposite should have been observed, e.g., during a high rate of firing with more rounds used, higher concentrations of combustible gases should have been observed.

Additional test data were examined on temperature, rate of firing, and concentration of combustible gases, as shown in Tables 14, 15, and 16. In all cases, lower concentrations of combustible gases were recorded at higher gun compartment temperatures when more rounds of ammunition were fired.

This data analysis suggests that sensitivity of the CSC model flammable gas detector might depend on the temperature of the environment, and since calibration of the instrumentation was carried out at temperatures different from actual test temperatures, reported data on percent LFL generated might be incorrect.

It was also suspected that differing ambient pressures due to the changes in flight altitude might cause incorrect detector response.

It is suggested that these postulates be verified experimentally by performing tests of detector response using known concentrations of combustible gases at low ($\sim$ 10° F), medium ($\sim$ 70° F), and high ($\sim$ 200° F) temperatures, together with appropriate pressure variations from sea level to 60,000-foot altitude.

Manufacturer's Review

The colored photographs, one of which is reproduced (in black and white) in Figure 64 were sent to the manufacturer of the sensors for his review and comment. In brief, his reply was that only a calibration test could be conclusive. The manufacturer's reply is shown in Figure 65.

Voids

One goal of the study was to identify any voids found. Two distinct areas in which full substantiating data could not be found were in sensor test and gun-gas analysis and test.

Gun-gas. Previous work on gun-gas has relied heavily on the similarity between gun-gas and its constituents and other known gases and mixtures. Analyses normally use experimental data on hydrogen, carbon monoxide, and methane as being valid for gun-gas since these three make up the major flammable constituents of gun-gas. However, properties such as actual percentages of mixture constituents, LFL, UFL, and the effects of the inert gases that also exist within the mixture have not been experimentally defined. Further, tests of purge systems have concentrated on verifying the safety of specific gun compartments and have not done enough to verify basic chemistry and thermodynamics of the gas-air mixture.

TABLE 14. FLIGHT TEST DATA*

Flight No. 59F	Temp (° F) Peak	Temp (° F) Avg	Fire Rounds	Fire Time,sec	Gas Concentration (% LFL) Peak	Gas Concentration (% LFL) Avg	Alt (1,000 ft)	Speed Knots
14	35	14	102	1.66	9	5	8	350
15	35	15	106	1.71	10	5	8	353
16	121	33	111	1.78	6	4	11	263
17	123	34	131	2.07	8	5	11	263

*Purge off

TABLE 15. FLIGHT TEST DATA

Gun Comp ΔTemp (° F)		Gas Concentration (% LFL)		Fire		
Peak	Avg	Peak	Avg	Rounds	Time (sec)	Flight No.
226	98	25	17	352	5.23	30F-2
228	88	22	11	272	4.09	23F-2
162	68	16	9	133	2.09	23F-4
141	49	12	7	319	4.76	35F-1
139	47	54	23	309	4.62	35F-2
123	44	42	17	242	3.66	27F-5
132	56	19	8	168	2.60	30F-1
164 Avg	64 Avg	27	13	256	3.86	
99	45	46	26	260	3.91	42F-1
92	42	56	30	259	3.90	42F-2
83	43	36	24	258	3.88	42F-3
91 Avg	46 Avg	46	27	259	3.90	

TABLE 16. FLIGHT TEST DATA

Gun Comp ΔTemp (° F)		Gas Concentration (% LFL)		Fire		
Peak	Avg	Peak	Avg	Rounds	Time,sec	Flight No.
288	87	22	16	212	3.23	67F-3
162	99	18	15	112	1.79	61F-6
145	65	20	12	150	2.34	63F-2
121	63	38	26	260	3.92	63F-1
179 Avg	79 Avg	22	17	184	2.82	
80	36	46	27	260	3.92	67F-1
71	32	54	34	260	3.92	67F-2
76 Avg	34 Avg	50	31	260	3.92	

CONTROL INSTRUMENTS CORPORATION

18 Passaic Avenue, Fairfield, New Jersey 07006 Tel. (201) 226-9366

July 1, 1977

Mr. W. A. Pace
Program Manager
Hazard Assessment Program
ROCKWELL INTERNATIONAL
LOS ANGELES AIRCRAFT DIVISION
International Airport
Los Angeles, California 90009

Dear Mr. Pace:

The pictures were reviewed and the following was noted.

Picture C1A - Active side, catalyst is slightly depleted (white aluminum oxide visible), reference looks like it was overheated.

Picture C1B - Appears normal.

Picture C1C - Active side, light color but o.k., reference side, ends are white indicating not an even coating.

Only calibration tests using flammable gas are valid for conclusive testing results.

Please contact me if you desire any additional information.

Very truly yours,

M. James Schaeffer

MJS:po
Enclosure

Figure 65. Manufacturer's review

Sensor. No tests have been found in which different sensors were tested together in a real environment, measuring gun-gas under gun-firing, gas-mixing conditions. The effects of temperature, humidity, and response time under calibrated conditions need to be better defined.

TEST DEFINITION

Because of the lack of data on some aspects of the gas sensor and corroborative test data on some phases of gun-gas analysis, tests were defined and procedures written to outline requirements and expected results.

It should be noted that the ultrasonic sensor as proposed by McDonnell Douglas was disclosed after this sensor test procedure was written. However, review of the McDonnell Douglas data indicates that there are still areas of concern that could be clarified by additional laboratory testing. Consequently, the ultrasonic sensor could well be added to the following test to more thoroughly evaluate various sensors.

Sensor Test

Background

The gun system installations in past and current military aircraft have been susceptible to the hazards associated with that volatile environment. The primary hazard has been fire and explosion in the gun bay caused by the accumulated gun gases. The predominate method of reducing the hazard of fire and explosion has been to use elaborate purge systems that flush away and/or disperse the combustible gases in a manner designed to maintain the gas concentrations below the combustible limits.

With the advent of higher rate of fire guns, the use of newer and more powerful propellants, as well as new gun compartment configurations, the need to determine the exact flammable concentration of the accumulated gases in real-time has become apparent.

One way to determine the real-time gun-gas concentration is to use a combustible gas sensor with its appropriate instrumentation. However, there is no current manufacturer of a combustible gas sensor specifically designed for use in an aircraft gun compartment. Rather, all such sensors were designed for use in nondynamic environments such as in mines or on oil rigs.

The combustible gas constituents, the rapid buildup and decline of gases, and the pressures and temperature gradients found in the gun compartments create scepticism about the adequacy of using the currently available sensors in an expensive high technology aircraft. The need to detect a lethal mixture requires very rapid sensor response without sacrificing the accuracy of the measurement.

Several ground and/or flight tests have recently been conducted using these conventional sensors. The A-10, F-15, and F-4 M-61/7200 rpm are the most recent. The A-10 and the F-4 tests used a standard catalytic gas sensor purchased from Control Instrument Company. Installation, instrumentation, calibration, and use were in accordance with the appropriate instruction manual provided by the manufacturer.

Since these tests were of interest and were closely related to work being performed under this contract, subsequent investigation and analysis of these test methods, equipment, and results have raised doubts concerning the use of these or similar sensors.

Questions have arisen concerning the adequacy of the response time needed by the sensor to detect the presence of a lethal mixture; the accuracy of the reading, especially with regard to the installation procedure (calibration, tube length, pumping technique); the effects of altitude (temperature and pressure), purge flow rates, and general performance.

The need to resolve these questions is readily apparent. If these sensors are adequate for this type of function, a proper test will verify their adequacy. If they are not adequate, this fact must be ascertained prior to widespread use and potential loss of aircraft and/or crewmembers from reliance on an inadequate instrument.

Approach

The overall objective of this effort is to provide the Air Force and industry with a capability for monitoring levels of flammable gases in the gun compartments of modern aircraft and to assure operational safety from gas combustion in such aircraft. To accomplish this objective, the following approach will be used.

1. A survey of commercially available combustible gas sensors will be undertaken. This will include evaluation of open and classified literature, consultations with manufacturers of monitoring systems and hardware, and contacts with users of such equipment. As a result of this evaluation, a number of operationally suitable detectors will be selected and their reported performance will be evaluated.

2. A test program will be undertaken to determine the performance characteristics and accuracy of selected detectors under environmental conditions expected to be found in gun compartments of modern aircraft. The sensors will be considered in a static and dynamic mode of operation. Principal parameters which affect performance and accuracy of combustible gas sensors onboard aircraft are

expected to be pressure, temperature, and proximity to maximum gas accumulation area. Effects of these parameters should be evaluated in detail as described in the following test program.

3. Based on the results of this test program, recommendations for selecting a sensor system for detecting explosive gaseous concentration onboard an Air Force aircraft will be advanced. Four principal alternatives will be considered in formulating such recommendations as follows:

    a. The use of the best-suited, onshelf commercially available detector without modification. This may require some degree of adaptation for onboard use. Adaptations might involve use of specially designed sampling and pumping provisions for the sensors, and some hardware installation in the aircraft for this purpose. Calibration corrections or correction factors may be required to properly interpret the output.

    b. Modification of commercially available detectors to suit the space and configuration existing in gun compartments of the aircraft. This would permit placing of the sensors in the most seriously affected areas and would provide for operation in a static mode with minimum hardware modification to the aircraft.

    c. Abandon use of commercially available sensors, and initiate a program to develop a gas sensor specifically designed for use in an aircraft gun compartment. Such a program would address and solve the environmental and dynamic gun gas detection problems associated with aircraft flight.

    d. Continue to use existing sensors.

4. Following the evaluation of the results of the test program, the most promising of the sensor candidates should proceed into development and qualification. This would identify problems and characteristics of the system in actual use, and, finally, would provide future users with a reliable, qualified gas sensing system.

The test program will be conducted in four phases, containing the following tasks:

- Phase I - Pretest preparation

  Task 1 - Review the market.

  Make a comprehensive investigation of currently available gas sensors, and make a preliminary evaluation of their potential for use as a test article.

Task 2 - Accumulate necessary articles.

Accumulate the desired test sensors and appropriate instruments along with the necessary literature. Note that the electrical/electronic components required to provide sensor readout must be tested in the same environment as the sensor.

Task 3 - Develop test procedures.

Develop the test procedure according to the instruction manuals for each sensor. Accumulate remaining articles.

Task 4 - Adapt test facility.

Design and adapt the test facility for simultaneous testing of several sensors under varying conditions.

- Phase II - Sea-level ambient sensor response tests

Task 5 - Calibrate instruments.

Calibrate all instruments according to their respective instructions for a known gas.

Task 6 - Vary D.

Vary the tube length (D) between the sensor and the test chamber.

Task 7 - Vary R.

Vary the flow pump rate (R).

- Phase III - Sensor altitude simulation response tests

Task 8 - Calibrate Instruments.

Calibrate all instruments according to their respective instructions for a known gas.

Task 9 - Vary D and R.

Vary the tube length (D) and flow rate (R).

Task 10 - Vary temperature.

Vary the test chamber temperature.

Task 11 - Vary pressure.

Vary the test chamber pressure.

• Phase IV - Evaluation of results

Task 12 - Evaluate Phase II.

Evaluate the results of Phase II tests.

Task 13 - Evaluate Phase III.

Evaluate the results of Phase III tests.

Task 14 - Recommendations and conclusions.

Make recommendations, based on Tasks 12 and 13 evaluations.

Task 15 - Documentation.

Documentation of the program.

The phase/task flow diagram is shown in Figure 66. Phase and task explanations are discussed in the following paragraphs.

Phase I, test procedure development and setup, is the preparation phase as described by Tasks 1, 2, 3, and 4.

Task 1 - Review the market. The initial step wherein all potential sensor candidates are identified and investigated by obtaining literature, contacting salesmen, manufacturers, etc. This preliminary evaluation of the potential use of each sensor in an aircraft gun bay will identify those sensors that will actually be tested in Phases II and III. During the Hazard Assessment study, Rockwell has thoroughly explored the possible candidate sensors; consequently, Task 1 would consist essentially of a review if performed by Rockwell.

Task 2 - Accumulate necessary articles. The sensors, their instruction manuals, and any instruments or equipment necessary for their installation and/or use will be acquired. In addition, any instruments or equipment needed for the testing in Phase II and/or Phase III will also be accumulated along with appropriate literature.

Task 3 - Develop test procedure. The actual step-by-step procedure to be followed during Phases II and III will be formulated. The test limits and parametric range will be established, as well as the physical layout of the test facility.

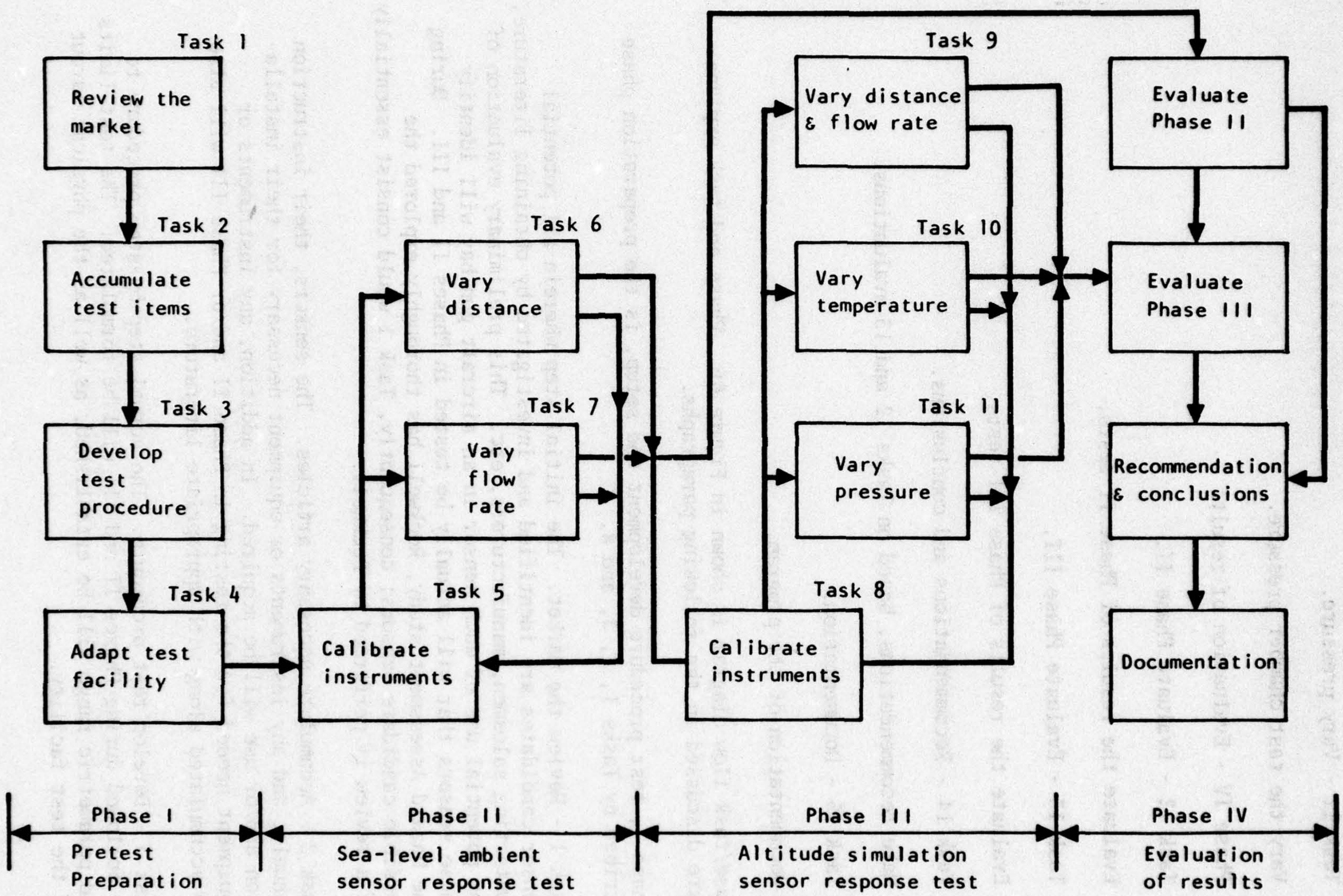


Figure 66.- Phase/task flow diagram.

Task 4 - Adapt test facility. The effort required to design and/or modify such items as the test chamber, if necessary, the adapters, or any other noncommercially available items. All the components will be arranged in an appropriate manner, and their proper functioning verified.

Phase II, sea-level ambient sensor response test, is the actual testing of the sensors to determine response time, response dynamics, and accuracy of each sensor to a known gas as a function of the gas type and quantity, tube length and flow rate. To accomplish this result, Tasks 5, 6, and 7 are performed in a cyclic manner to establish a good parametric set of data. (See Figure 67.)

Task 5 - Calibrate instruments. Calibration of the instruments according to their respective instruction manuals.

Task 6 - Vary D. Varying of the tube length (D).

Task 7 - Vary R. Varying of the flow rate (R).

Phase III, sensor altitude simulation response tests. Testing of the sensor under simulated altitude conditions. As in Phase II, the tasks in Phase III are performed in a cyclic manner to establish a good parametric data base as a function of tube length, flow rate, temperature, and pressure. (See Figure 68.)

Task 8 - Calibrate instruments. Same as Task 5.

Task 9 - Vary D and R. Same as Tasks 6 and 7.

Task 10 - Vary temperature. Vary temperature in accordance with altitude values.

Task 11 - Vary pressure. Performed in conjunction with the temperature. Each altitude has a pressure/temperature pair.

Phase IV, evaluation of results. The final phase. Encompasses tasks related to analysis, evaluations, recommendations, conclusions, and documentation.

Task 12 - Evaluate Phase II. The analysis and evaluation of the test results from the Phase II test procedures.

Task 13 - Evaluate Phase III. The analysis and evaluation of the test results from the Phase III test procedures.

Task 14 - Recommendations and conclusions. Based on the findings of Tasks 12 and 13.

Task 15 - Documentation. A summary of the work performed.

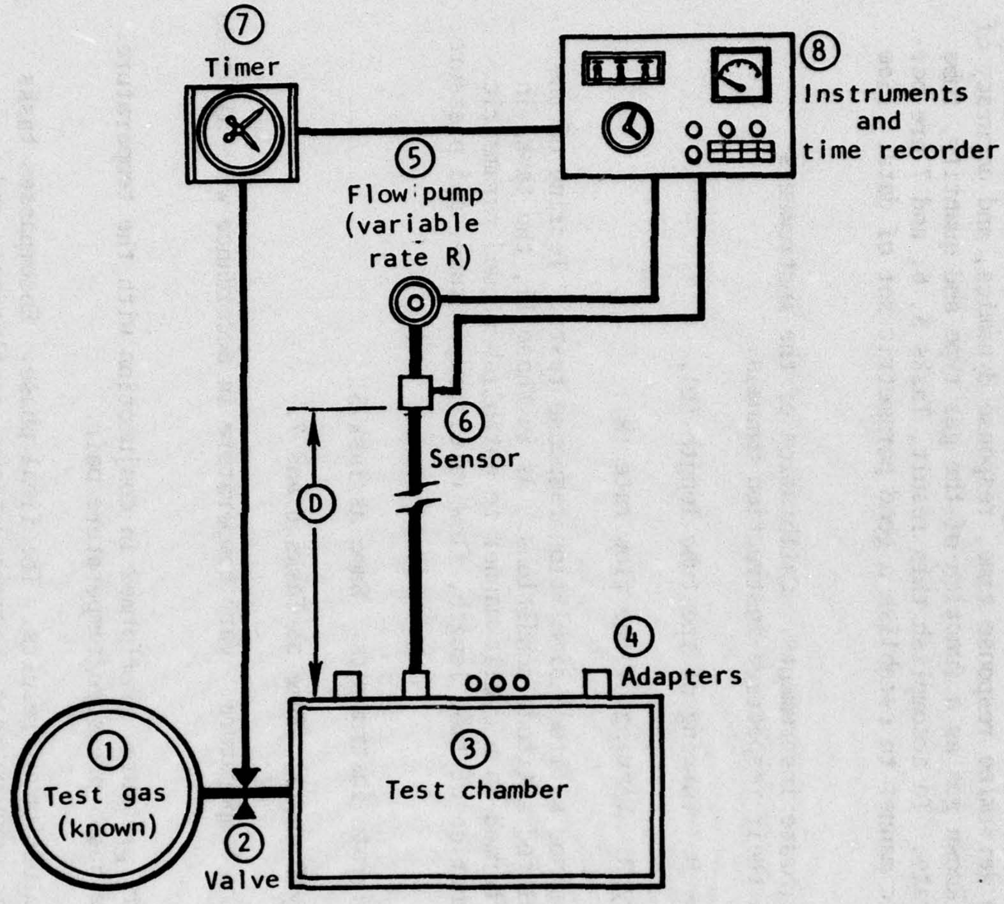


Figure 67. Gas detector test schematic - phase II.

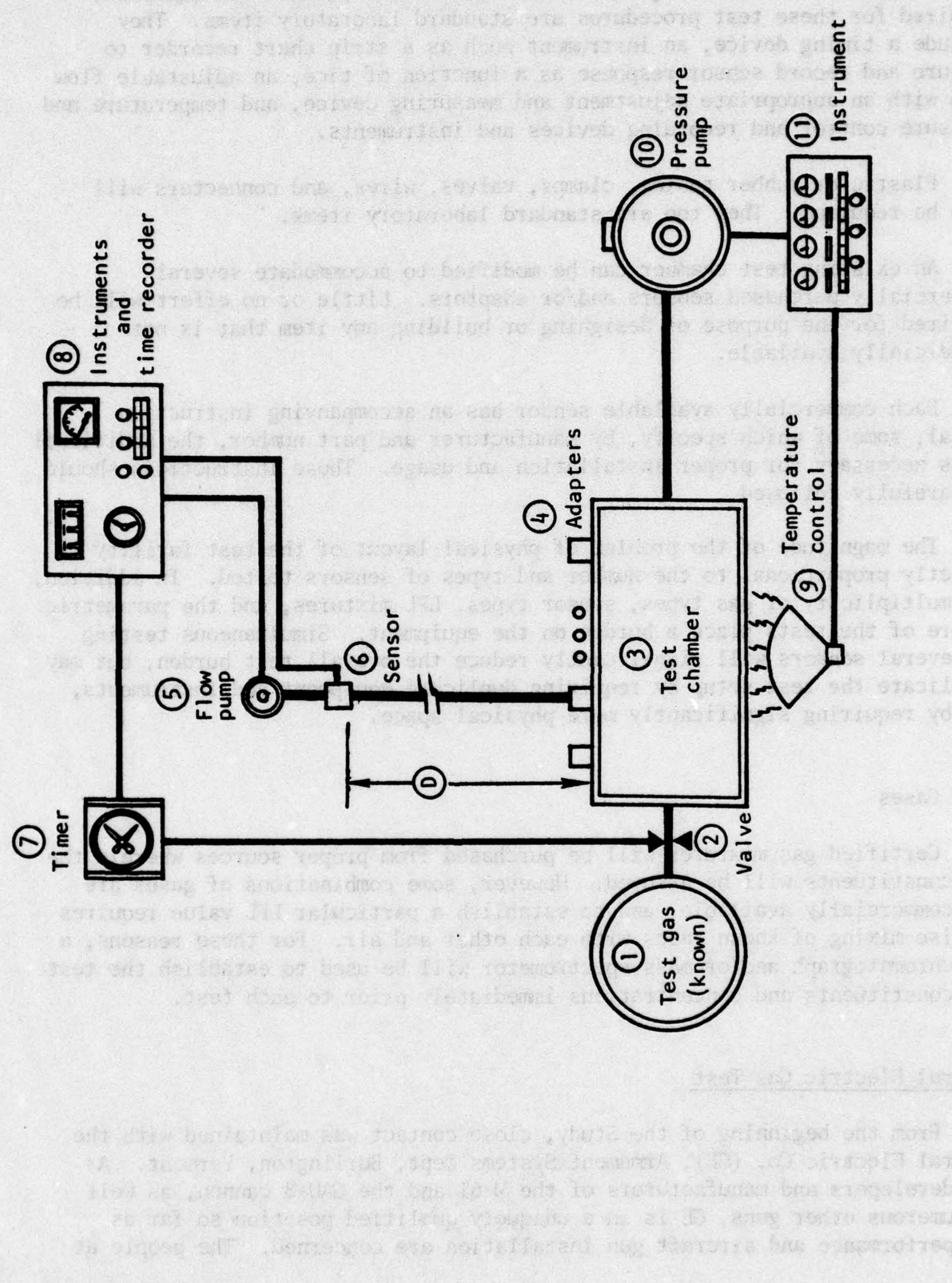


Figure 68. Gas detector test schematic - phase III.

Instrumentation and Equipment

As can be seen from Figures 67 and 68, the instruments and equipment required for these test procedures are standard laboratory items. They include a timing device, an instrument such as a strip chart recorder to measure and record sensor response as a function of time, an adjustable flow pump with an appropriate adjustment and measuring device, and temperature and pressure control and recording devices and instruments.

Plastic or rubber tubing, clamps, valves, wires, and connectors will also be required. They too are standard laboratory items.

An existing test chamber can be modified to accommodate several commercially purchased sensors and/or adaptors. Little or no effort will be required for the purpose of designing or building any item that is not commercially available.

Each commercially available sensor has an accompanying instruction manual, some of which specify, by manufacturer and part number, the additional items necessary for proper installation and usage. Those instructions should be carefully followed.

The magnitude of the problem of physical layout of the test facility is directly proportional to the number and types of sensors tested. In addition, the multiplicity of gas types, sensor types, LFL mixtures, and the parametric nature of the tests place a burden on the equipment. Simultaneous testing of several sensors will significantly reduce the overall test burden, but may complicate the test setup by requiring duplicate equipment and instruments, and by requiring significantly more physical space.

Test Gases

Certified gas mixtures will be purchased from proper sources wherein the gas constituents will be assured. However, some combinations of gases are not commercially available, and to establish a particular LFL value requires precise mixing of known gases with each other and air. For these reasons, a gas chromatograph and/or mass spectrometer will be used to establish the test gas constituents and concentrations immediately prior to each test.

General Electric Gas Test

From the beginning of the Study, close contact was maintained with the General Electric Co. (GE), Armament Systems Dept, Burlington, Vermont. As the developers and manufacturers of the M-61 and the GAU-8 cannon, as well as numerous other guns, GE is in a uniquely qualified position so far as gun performance and aircraft gun installation are concerned. The people at

GE provided reports and technical data, answered questions, and in general, offered the full cooperation of their engineering staff. As the need for substantiating tests became apparent, joint test efforts were discussed.

Under company funding, GE decided to conduct a series of gun-gas tests in which they would draw the gas emitted from an M-61 gun into an evacuated chamber and then analyze the constituents of the gas. This test could provide significant validation of gas analyses by measuring the amount of gas as a function of time and determining the constituents of the mixture under controlled conditions.

The possibility of a joint test effort between Rockwell and GE was discussed. The results were positive. Consequently, a tentative SOW was prepared and submitted to GE for review and comment. It was assumed that this test could be conducted as a part of a larger GE test and therefore facility and setup charges would be minimal. Further, it was assumed that gun and ammunition could be obtained from the Government at no cost. These were preliminary discussions and AFAPL was fully informed. No commitments were made by any of the parties.

It was impossible to conduct the tests during the short time remaining on the study. Accordingly, no further action was taken.

The need for this kind of test remains, and it is strongly recommended that it be considered in the future. Should GE decide to conduct their tests, it would be an ideal opportunity to validate study results.

HAZARDOUS MATERIALS

Approach

In addition to the gun-gases, other flammable materials may be present in or near the gun compartment. Although the routing of fuel lines through the bay would seem to be an undesirable practice, it cannot always be avoided, therefore a fuel leak in the compartment would always be a possibility. Also, since many gun systems are hydraulically operated, hydraulic fluids will be present.

Data were obtained on the flammability characteristics of representative fuels and hydraulic fluids. The data were examined to evaluate the extent of the hazard associated with the fluids.

The flammability of fluids which may be present in or adjacent to the gun compartment has been addressed in a number of studies and experiments. The ignition hazard level depends to a large degree on the ignition properties of the combustibles when exposed to different types of heat sources. These

properties include behavior during ignition by electrical sparks or arcs, autoignition in uniformly heated containers, ignition by hot surfaces, and ignition by hot gases. Results of these studies were thoroughly documented in Reference 42.

The minimum autoignition temperatures are time dependent, and those shown in Table 17 are based on maximum time delays. The high temperatures associated with the gun compartment are often of very short duration; accordingly, the autoignition temperatures may be correspondingly higher than those shown in Table 17.

The AIT's are also significantly affected by ambient pressure and thus flight altitude. The AIT's of all the combustibles listed in Tables 17 and 18 are higher with increased altitude.

TABLE 17. PROPERTIES OF HYDRAULIC FLUIDS (REF 42)

Fluid	Flash Point (° F)	Minimum AIT (° F)
Hydraulic Fluid		
MIL-H-5606C H-515 OHA (mineral oil)	195	437
MIL-H-83282 MLO-73-93	385	670
Chevron M2V MLO-71-45	208	698
MIL-2190 (mineral oil)	450	665
Mobil DTE 103 (mineral oil)	390	702
Cellulube 220 (phosphate ester)	455	1038
Harmony 44 (mineral oil)	460	680
Houghto-Safe 271 (water glycol)	–	767
Houghto-Safe 1055 (phosphate ester)	505	1020
Pydraul 150 (phosphate ester)	380	975
Pydraul AC (chlorinated ester)	450	1148
Skydrol (phosphate ester)	360	>1300

TABLE 18. AVIATION FUEL FLAMMABILITY (REF 42)

Fuel	Flash Point (° F)	AIT in Air (° F)	Flamm Limits in Air LL Vol (%)	UL Vol (%)
JP-1	115	440	–	–
JP-3	–	460	1.4	7.9
JP-4	~ 0	445	1.3	8.0
JP-5	150	435	0.6	4.5
JP-6	100	450	0.7	4.8
JP-8	115	435	0.8	4.9
Jet A	105-140	435	Similar to JP-8	
Jet B	~ 0	450	Similar to JP-4	
Gasoline 100/130	-45	825	1.3	7.1
Kerosene	125	480	0.7	4.8

Hydraulic Fluids

Because hydraulic power is used in conjunction with many armament systems, various hydraulic fluids may be present in gun compartments. The hydraulic fluid which is most commonly used in existing military aircraft is MIL-H-5606B hydraulic oil. Unfortunately, it has a low flash point, fire point, and autoignition temperature, so a search for fluids with better flammability characteristics has been pursued for some time. The most promising ones are derived from mineral oils or are synthetic fluids such as phosphate esters. All have varying penalties in terms of cost, availability, special seal requirements, and impact on operational logistics, but their improved flammability characteristics make them attractive. Table 17 contains a list of currently used fluids and promising ones which are under development.

In general, the vapor pressures of these materials are low. They are made up of high-molecular weight materials because they are designed for use at elevated temperatures and pressures. However, they are flammable at ordinary temperatures and pressures as mists, and autoignition may occur if the residence or contact time is long enough. Even at atmospheric pressure, relatively low temperatures could ignite a hydraulic fluid if enough vapor or mist is present. Since gas/air temperatures is high as 1,900° F (Reference 29) have been measured in gun compartments and barrel temperatures run as high as 1,000° F (Reference 31), igniting hydraulic fluid which might leak into the compartment is a distinct possibility.

Fuels

Jet fuels are extremely hazardous materials especially in the vicinity of potential ignition sources such as a hot gun barrel or breech exhaust gases. The lower flammability limit of JP-4, for example, is much lower than that of the gun-gases. Table 18 lists flammability limits and AIT's for a number of jet fuels.

Under equilibrium conditions of fuel vapor/air concentration, the specification fuels have flammability limits which are temperature and altitude dependent. Figure 69 compares JP-8 fuel and flammable mists with JP-4 fuel. It should be recognized that the data shown are only representative of typical fuels and that both the upper and lower flammability limits for individual fuels can vary within bands established by their specifications.

Thus, where fuel lines are routed through or near gun compartments, the possibility would always exist that fuel vapor or liquid could contribute to an unfavorable flammability situation. To minimize this problem, every effort should be made to keep these materials out of gun compartments.

Lubricating Oils

Table 19 lists typical lubricating oils and their combustion properties.

TABLE 19. PROPERTIES OF LUBRICATING OILS (REF 42)

Lubricating Oils	Flash Point (° F)	Minimum AIT (° F)
MIL-L-7808G 0-148 LGT (sebacate-adipate diester)	405	728
MIL-L-23699B 0-156 (polyester)	440	725
Monsanto OS-124	550	1112
SAE No. 10	340	720
SAE No. 60	480	770

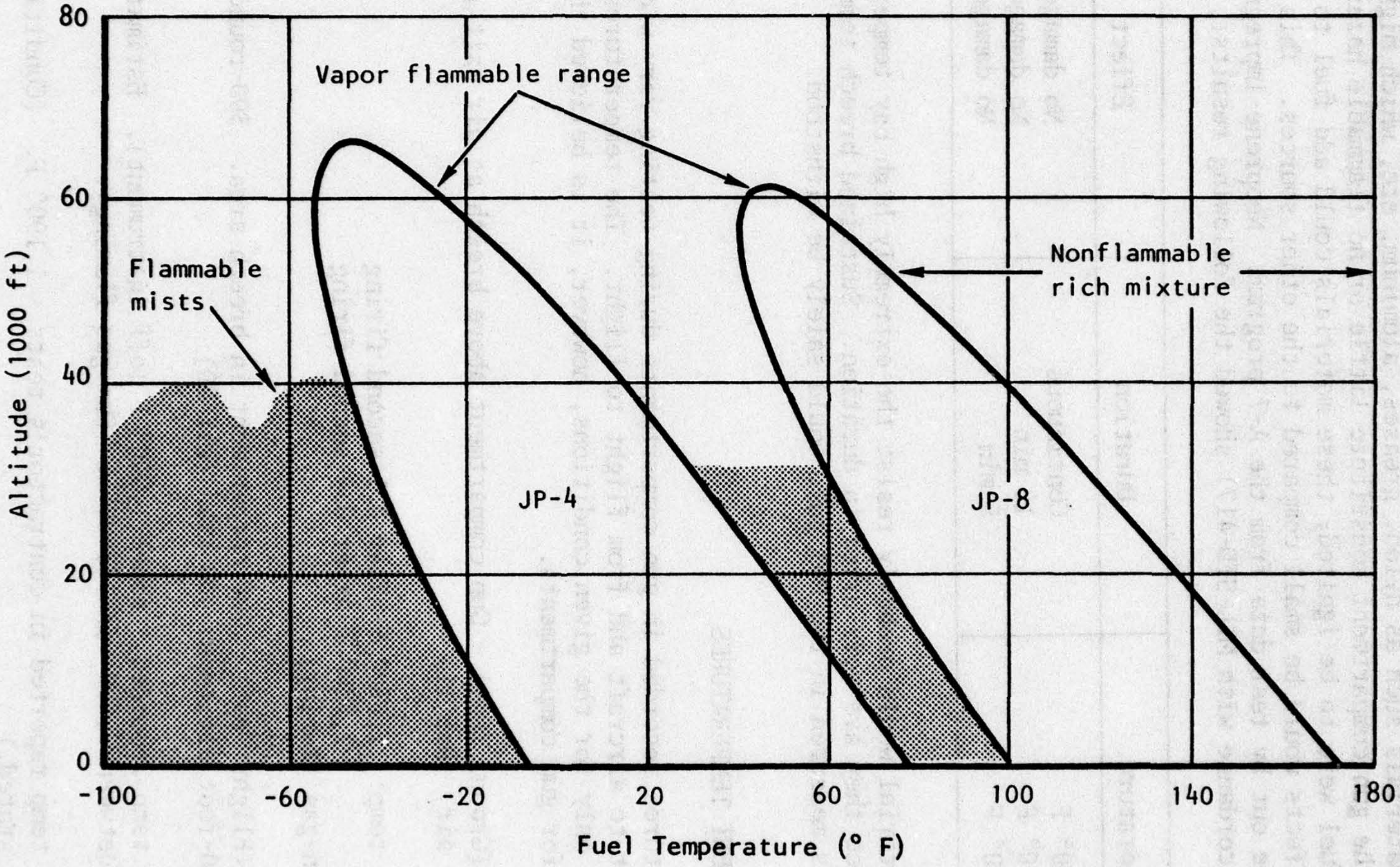


Figure 69. Static flammability limits of fuels of different volatility (Reference 44).

Other Materials

Other materials such as nylon, greases, aluminum, etc, which might be present in the gun compartment constitute little or no flammable hazard. If gun-gas or fuel were to be ignited, these materials could add fuel to the fire, but their effects would be small compared to the other sources. This conclusion is borne out by test data from the A-7 program. Neoprene-impregnated nylon (in accordance with MIL-STD-417) showed the following results:

Temperature	Duration	Effect
180° F	Continuous	No damage
250° F	10 min	No damage
500° F	5 min	No damage

This material would probably resist the extremely high bay temperatures recorded since they are very brief in duration. Sustained breech temperatures of 147° F, as measured in the M61 gun, could safely be withstood.

GUN COMPARTMENT TEMPERATURES

Temperatures recorded in gun compartments during testing vary widely, from aircraft to aircraft and from flight to flight. The temperatures listed are specific only for the given conditions, however, it is believed that they are typical for gun compartments.

- F-15 (Ground Test) - Gun compartment above breech at air exit (no purge air) (Ref 11)

  - Max temp: 1,050° F after 0.1-second firing
    1,580° F after 0.4-second firing
    (Gun-gas flaming)

- F-14 (Flight Test) - Gun compartment in breech area. 300-round burst, 15,000-foot altitude, 400 kias (Ref 29)

  - Max temp recorded - above 1,900° F (off instrument). Estimated to be between 2,000° and 3,000° C (Gun-gas flaming).

  - Max temp reported in contractor's tests - 1,190° F. (Conditions not stated.)

  - Gun compartment after 50-round burst, M0.51, 3,000-foot altitude. Max temp recorded - slightly under 1,000° F.

- A-10 (Ground and Flight Tests) (Ref 12)

  - Max temp recorded (conditions unstated) - 340° F above gun barrels. 310° F for 6 seconds at forward end of breech.

- M-61 Gun (Ground Test) (Ref 32)

  - Max temp at 7,200 spm.

    Housing - 117° F after firing 117 rounds
    Barrel - 497° F (Temp Rise = 380° F) after 625-round burst

- M61 Gun (Average barrel temperature after firing)

  Reference 31

  1,200 rounds - 1,000° F Temp Rise
  750 rounds - 830° F Temp Rise
  600 rounds - 725° F Temp Rise

  Reference 33

  660 rounds - 489° F
  (7,200 spm) total temperature

  Housing temperature after firing

  Reference 31

  750 rounds - 120° F Temp Rise

  Reference 33

  600 rounds - 147° F
  (7,200 spm) total temperature

- Case temperature (The ejected fired case has been measured at 300° to 400° F in the main body (Reference 31).

COOKOFF TEMPERATURES

Ammunition cookoff, in which a round explodes from excessive heat, normally occurs in a gun after long firing with attendant high gun chamber and barrel temperatures. However, high temperatures on the ammunition in the feed and storage system can also cause cookoff. In at least one case, improper operation of the purge and ECS system of an aircraft during ground maintenance did result in several rounds cooking off in the gun compartment.

The process is heavily time-dependent. Even after the cookoff temperature is reached, some time elapses before the round goes off. Normally, guns have an automatic clearing device to empty hot chambers at the end of firing. In case of a malfunction, it may not be possible to clear the gun and cookoff may occur.

Experiments conducted with the M-197 gun and the M56A3 20mm ammunition (Olin WC870 propellant) show that a burst of 348 rounds will induce cookoff in 2 to 4 minutes after the end of the burst.

Propellant will cookoff after exposure to 360° F for 4 minutes (not substantiated by gun firing tests) (Reference 34).

The M-61, 20mm gun reaches ammunition cookoff temperature after firing approximately 480 rounds (assuming an initial barrel temperature of 75° F). This is based on test data (Reference 31).

TASK 3 - DESIGN CRITERIA

GUN COMPARTMENT DESIGN CRITERIA

It is clear from the review of pertinent specifications, program requirements, test results, and operational experience that was accomplished during the study, that there is considerable latitude in establishing gun-gas purging requirements. Future gun installations will most likely be designed under similar flexible criteria.

It has been shown that existing military specifications and handbooks are precise in their limitations:

- DH2-5, Keep gas-air mixture out of explosive range.

  LFL = $\sim$ 9 percent by volume.

- MIL-HDB-244, Prevent accumulation of gun-gas between 10.5 and 72 volume percent.

- MIL-I-8670 (AS), Fire 100 rounds or 6-second burst (whichever is greater) without exceeding 90 percent of LFL.

- MIL-T-5029, Fire 100 rounds per gun minimum at 1,000- and 2,000-foot altitude, at 150 to 200 kias without exceeding 60 percent of LFL.

- Navy Handbook 221, Do not allow gas-air mixture within gun compartment to fall within explosive range. LEL of gun-gas is approximately 9% by volume. Provide sufficient ventilation to result in 4.5% combustibles - good mixing; 2.25% - less thorough mixing.

Nevertheless, it has also been shown that many present day aircraft were designed to other criteria. The maximum feasible purge air flow combined with a vent ratio which will prevent damage if combustion does occur is the most prevalent design philosophy. The successful operational employment of these aircraft is solid evidence of the validity of the theory.

Gun-gas purge requirements are the responsibility of the individual SPO's. They can specify bay volume, vent ratio, airflow and all other design requirements to provide the desired mission effectiveness. The role of ADTC and AFATL is to provide advice based on experience (Reference 35).

PURGE EFFECT ON GUN COMPARTMENT DESIGN

The often repeated refrain that aircraft design is a series of tradeoffs is probably nowhere more obvious than in gun compartment design. The restrictions and trades vividly affect the purge system.

In practical terms, often the gun and ammunition complement, as well as the aircraft mold lines, are specified. Bay shape and volume are thus restricted. The need for line and component space is acute. Since the gun is often in the nose, the radar, avionics packages, and other sensors compete with the gun and ammunition for space. The result is a bay crammed with equipment and with flow paths not conducive to good air circulation.

Purge air may be introduced by two means; ram air from the exterior, or bleed air from either engine or ECS, or both. The amount of ram air depends on the size and location of the ram-air inlet. Both size and location are severely restricted by opening force requirements and drag from the open door. Bleed and ECS air place severe demands on the aircraft system because the need is for large quantities of air in a very short time. This demand may momentarily starve other important systems such as the cockpit.

The result of this dichotomy must be a purge system that will permit gun firing throughout the flight envelope of the aircraft. Limiting the aircraft in air speed, altitude, or maneuver due to gun firing restrictions is unacceptable.

Experience shows that the best way to achieve this goal is to analyze carefully, make assumptions based on experience, and test the resulting system carefully to validate the analysis and assumption.

Practical application of the vent ratio/overpressure relationship may be seen in Figure 70, which was prepared by Northrop Corp for the YF-17. The aircraft was designed to a vent ratio of 4. As shown, the maximum overpressure, which includes the effects of ram air as well as posible gun-gas combustion, never reached the gun bay design overpressure which was 4 psi. While

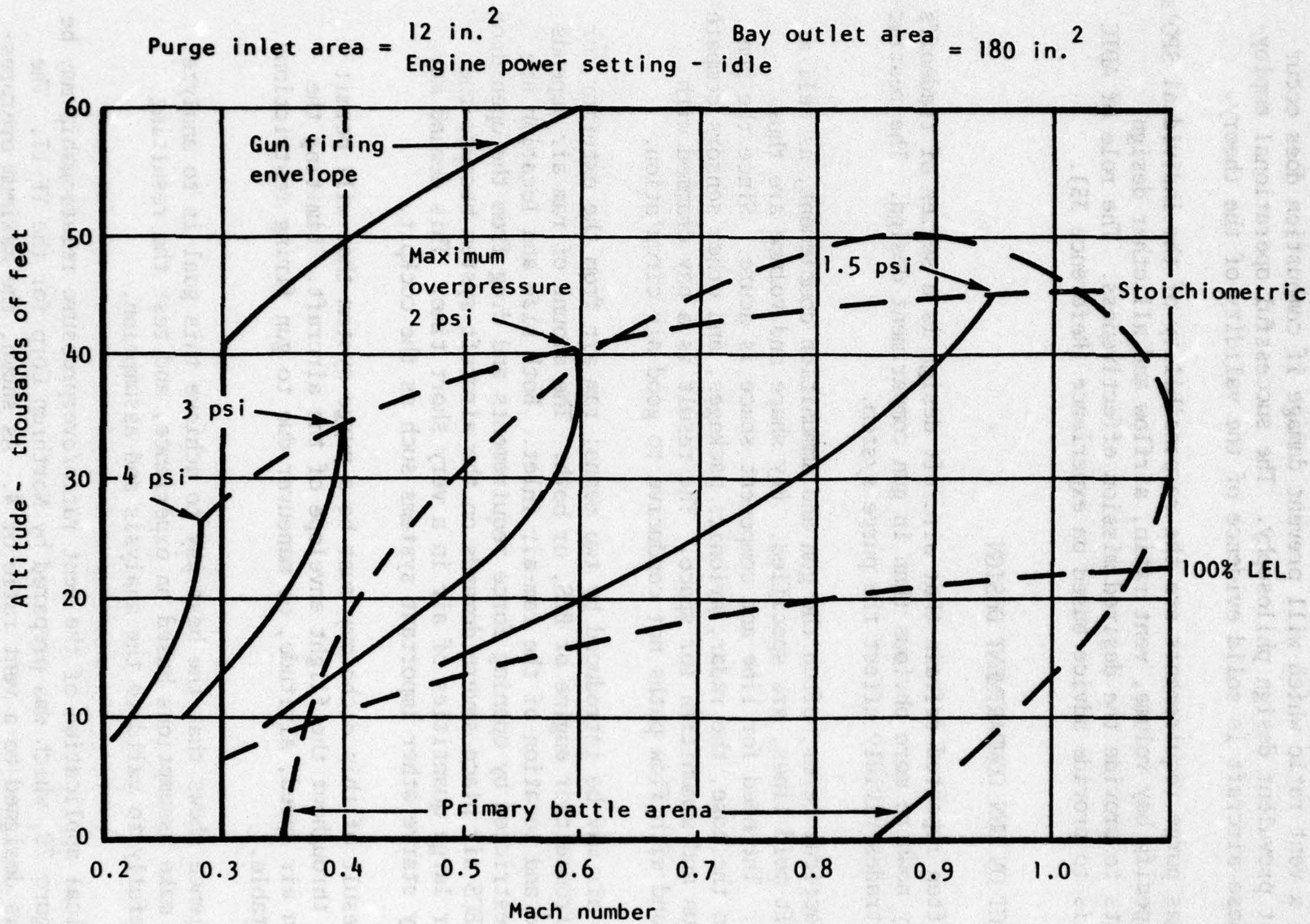


Figure 70. Gun bay purge performance.

subsequent flight testing showed that the LFL was exceeded at times, the basic design philosophy which was to maintain gun-gas concentrations below LFL at lower altitudes and to prevent overpressure due to burning gun gases from exceeding compartment design limits at higher altitudes (Reference 36) was validated.

Further demonstration of the vent ratio theory in gun compartment design may be found in a design study which investigated the feasibility of installing the 30/25mm gun in the F-15. This gun was a modified GAU-8, firing 25mm cased ammunition. The gas energy from this gun would be considerably greater than the M61 which the F-15 presently carries, consequently, gas purging would be correspondingly more critical. Nevertheless, the study concludes that a passive purge system with fixed louvered vent areas sized to allow explosion of a stoichiometric mixture of gun-gas within the gun compartment without damage to aircraft structure would be satisfactory. This would also be true for the standard GAU-8 30mm cannon. (Reference 40.)

Gun Compartment Design Validation

Experience with the F4E and the F-15 provides evidence that the design theory of providing maximum purge air flow possible is fundamentally sound. Both of these aircraft have undergone recent tests in which the M61 gun was up-rated from its normal firing rate of 6,000 to 7,200 spm. Final reports on these tests have not been issued, but informal discussions with Air Force test personnel show the following:

F4E. The aircraft was ground and flight tested at Eglin AFB, with the M61 firing 7,200 spm. At no time did the gun-gas exceed 8 percent LFL in the gun compartment. All tests were deemed successful (Reference 37).

NOTE: The catalytic sensor was used to record gas concentrations.

F-15. The aircraft was ground and flight tested at Edwards AFB, with the M61 gun firing 7,200 spm. Gun-gas concentrations in the gun compartment were within safe limits and all tests were satisfactory. (Reference 38.)

Subsequently, motion pictures of F-15 high-rate air firing were viewed. During the burst, a sizable fire ball formed in the upper wing surface near the leading edge. The fireball persisted until the gun stopped firing. There was no damage since the fireball was aft of the engine inlet and the wing upper surface was able to withstand the short duration of the fireball. Conditions were 180 KIAS, 10,000 feet, straight and level. Burst length was 750 rounds. These pictures are evidence of the amount of combustible gas that is emitted during high-rate M61 firing. (Reference 39.)

DESIGN TECHNIQUES

There are design techniques that can inherently reduce the possible hazards in the gun compartment. Recognition of the potential hazards early in the design stages and implementation of counter techniques can materially reduce subsequent problems. Some of these techniques are:

1. Strive to keep everything out of the gun compartment that is not necessary for storage, feeding, and firing the guns.

2. If it is necessary to route fuel and hydraulic lines in the compartment, they should be protected against possible gas combustion by double-wall construction or similar protection.

3. Shield electrical cables against possible gas combustion.

4. If fuel tanks are adjacent to the gun compartment, double-wall construction and adequate sealing should be used between compartments.

5. Use the system safety program to identify possible hazards and ways to prevent them.

6. Conduct a thorough test program to validate the safety and efficiency of the design.

7. Consult the Design Handbooks, References DH2-5 and DH1-6, for more detailed advice.

GUN COMPARTMENT DESIGN CRITERIA SURVEY

The study of gun compartments would not be complete without a look at the many successful gun-carrying aircraft of the present and recent past. Accordingly, a survey was made of the pertinent design criteria which was used to design, develop, and operate these aircraft. A matrix form was prepared and sent to the following firms:

Grumman Aerospace Corp - F-14
McDonnell Aircraft Co - F4, F-15, F-18
Northrop - F5, YF-17
General Dynamics - F-111, F-16
Vought - A-7
Fairchild Republic - A-10, F-105

A sample letter is shown in Figure 71. As shown in Figure 72, the response was excellent. Information was received on the F-5, YF-17, F-105, F-4E, F-15, F-18, A-7, and A-10. In the figure, the information listed under the various headings was provided by each individual firm on its own aircraft. The result gives a good illustration of the basic design principles in the gun compartments of the various aircraft.

August 12, 1977

Mr. T. R. Rooney
Manager, Aircraft Engineering
Northrop Corporation
3901 W. Broadway
Hawthorne, California 90250

Dear Sir:

The attached form lists information needed to complete an aircraft gun hazard study which Rockwell International, under contract to the Air Force Aero Propulsion Laboratory, is conducting.

This study, which is entitled, "Hazard Assessment of Aircraft Gun Compartments" is under the cognizance of R. G. Clodfelter, AFAPL/SFH. It has been underway since May 1976. The objectives of the study were to acquire historical data on aircraft gun compartments, analyze the data, develop a methodology for assessing the hazards, and prepare design criteria for the DH2-5, Armament Handbook. Primary emphasis has been on gun gas.

In the final report, preparation of which has just begun, we would like to include a matrix such as the attachment detailing the design criteria of recent gun-carrying aircraft.

Your providing the information needed to complete this form for the YF-17 and F-5 would contribute to the authenticity and thus the value of the study results. We would, of course, acknowledge the data source and, if you wish, send you a copy of the draft report for your review and comment.

We have had excellent cooperation from you and other contractors in obtaining information during this program. We look forward to receiving your response to this request.

Very truly yours,

Rockwell International
Los Angeles Division

W. A. Pace, Program Manager
Advanced Systems Design

WAP/jak

Figure 71. Sample letter requesting program information.

Aircraft	Mfg	Gun		Gun Bay			Purge system		
								Max airflow	
		Type	No.	Free Volume	Vent Ratio	Overpressure	Type	Injector	Ejector
F-5E***	Northrop	M39A2 or M39A3	2 right & left sides	9.75 ft^3 per gun	2.0* $\frac{ft^2}{100\,ft^3}$	Max expected at medium altitude loiter airspeed 3.5 psig	Ram air	Ram flow 2.8 lb/sec max mach std day 5,000 ft per gun	None
F-5F***	Northrop	M39A2 or M39A3	1 left side only	6.73 ft^3	7.2** blowout doors full open 3.3 blowout doors full closed	Max expected at low altitude min airspeed 3.3 psig	Ram air	Ram flow 4.8 lb/sec max mach std day 5,000 ft	None
YF-17***	Northrop	M-61	1	31.2 ft^3	4.0	4.0 psig at low altitude min airspeed	Ram air through bay with breech scavenge ejector	Ram flow 5.4 lb/sec at max mach std day sea level	12 lb/min Primary flow, 75 lb/min Secondary flow
A-10****	FRC	GAU-8/A 30mm	1	56.0 ft^3	2.24	2.5 psig	Sonic ejector		Primary 0.152 lb/sec[1]
							Scavenge air inlet-60 $in.^2$ capture area	239 lb/min (1)	Secondary 60 lb/sec
F-105****	FRC	M61-A1 20mm	1	21.0 ft^3	1.55	5.4 psig	Supersonic ejector		Primary 0.063 lb/sec (2)
							Scavenge air inlet-3 $in.^2$ capture area	36 lb/min (2)	Secondary 1.27 lb/sec

NOTE: 1. Values at design condition: 150 ktas, 10 kft. Scavenge airflow is continuous. Ejector operation initiates with gun firing and terminates 30 seconds after gun firing. Ejector deleted from A-10 when compartment gas concentration measurements proved it unnecessary. Scavenge air inlet and compartment outlets sufficient for A-10 design.

2. Values are for system maximum performance condition: Maximum afterburner at sea level. Scavenge airflow initiations with gun firing and terminates 30 seconds after gun firing. Ejector operation initiates with gun firing and terminates 5 seconds after firing.

*F-5E gun bay door panels permit an increase in vent ratio with pressure buildup and prevent overpressure from exceeding structural limits.
**F-5F blowout doors open at 3 psig above local static.
***Courtesy Northrop Corp.
****Courtesy Fairchild Republic Co.

Figure 72. Aircraft gun compartment hazard assessment.

Aircraft	Mfg	Gun Type	Gun No.	Gun bay Free volume	Gun bay Vent ratio	Overpressure	Purge system Type	Max airflow Injector	Max airflow Ejector
F-4E*	MCAIR	M61A1	1	23 ft^3	2.72 $\frac{ft^2}{100 ft^3}$	5 psig	Ram/ejector	250 lb/min ram (est)	12 lb/min (primary flow) 40 lb/min (secondary flow)
F-15*	MCAIR	M61A1	1	39 ft^3 (Total compartment)	3.47	5 psig	Louvers only	Not determined	N/A
				13 ft^3 (Gun compartment only)	8.28				
F-18*	MCAIR	M61A1	1	30 ft^3	4.50	4 psig	Ram ejector	440 lb/min ram (calc.)	12 lb/min (primary flow) 75 lb/min (secondary flow)
F-14A**	Grumman	M61A1	1	15 ft^3	4.86	5 psig	Conditioned air from environmental control system at 35° F/0° F	40K 23 lb/min 30K 24 lb/min 20K 27 lb/min	
A-7D*** A-7E	Vought	M61A1	1	14 ft^3 (3)	5	Gun bay: -3 psig (min airspeed, max throttle) to +0.5 psig (max airspeed, min throttle), purge air door open Ammo bay: -1.5 to +0.5 psig (same conditions as above)	Bleed-air purge. Engine bleed airflow to compartments. Breech shroud restricts gas flow from gun area. Gas/air mixture ejected through actuated door.		4 lb/min at low engine power min speed high altitude (min) 75 lb/min at max speed sea level

NOTE: 3. Includes shroud volume.

*Courtesy McDonnell Aircraft Co.
**Courtesy Grumman Aerospace Co.
***Courtesy Vought Corp.

Figure 72. Aircraft gun compartment assessment (concluded).

SECTION IV

CONCLUSIONS

GENERAL

On the basis of the historical data reviewed and the analyses performed during the study, the following conclusions have been drawn.

1. Statistically, there is a very small chance that a modern fighter aircraft will be seriously damaged by a gun-gas explosion or fire in flight.

2. The fact that there have been so few in-flight gun-gas incidents is a tribute to the ingenuity of and cooperation between designers, test personnel, and operating agencies.

3. At least one fighter has a gun-gas problem so severe that the burst length is limited. This is unacceptable during combat conditions.

4. Combustion of the gun-gas emitted by a modern rapid fire cannon can develop overpressures within the gun compartment high enough to destroy the aircraft. In MIL-STD-882 terms, the hazard rating may be expressed as class III, critical, to class IV, catastrophic.

5. The methodology developed during the study can, with judgment, be applied to existing or conceptual gun installations to determine the Hazard Index as related to a baseline installation which was determined from operational experience.

6. Instrumentation for measuring the flammability of gun-gas is available, although it is not, on the evidence of the data reviewed herein, possible to verify the accuracy under some conditions of temperature and response time. A new ultrasonic sensor technique employing different detection and measurement principles is being developed.

7. A test program is needed to calibrate and qualify gun-gas sensors.

8. A test program is needed to duplicate and verify the gun-gas analysis.

9. Review of A-10 and F-15 operational statistics at a future date and comparison with the predicted data in the methodology would enhance the value of the study.

10. More definitive cause/result descriptions would enhance the value of the NISC accident/inspection data which were used herein.

In modern, high-performance aircraft, reduction of the hazards due to gun-gas concentration in the gun compartment by airflow alone does not appear to be a feasible approach. Because of the irregular shapes of the compartments and the effect of the installed equipment on gas/air circulation, airflow paths cannot be accurately defined. Thus, there will always be imperfect mixing of the purge air with the gun-gas so there will be layers and/or pockets in which gas concentrations may be higher than desired. However, because of temperature distributions within the compartment and flame speed characteristics of the gases, especially at altitude, sustained burning even in the event of ignition does not seem likely.

An optimum design would be one which combines adequate venting and a reasonable purge airflow rate with an allowable pressure rise in the compartment. This could be achieved from trade-offs which minimize degradation in aircraft performance while accepting spurious combustion in the compartment by providing a vent ratio of approximately five and a reasonably high purge airflow rate.

APPENDIX

DESIGN HANDBOOK DH 2-5

ARMAMENT

DRAFT/OUTLINE OF PROPOSED SECTIONS

Section 2A Hazard Analysis

Design Note 2A1 - Hazard Analysis Program

Design Note 2A2 - Hazard Analysis

1. Introduction

2. Situational Example

3. Operational Aspects

4. Methodology and Elements

4.1 Flight/Mission Parameters

4.2 Hazard Forces/Environment

4.3 Hazard Condition Data

4.4 Preliminary Hazard Assessment

4.5 Safety Enhancement Studies

4.6 Safety/Survivability Enhancement Techniques

4.7 Trade Studies

4.8 Detailed Hazard Assessment

4.9 Validation Testing Criteria

DESIGN NOTE 2A2 - GUN COMPARTMENT HAZARD ANALYSIS

1. INTRODUCTION

A gun compartment hazard analysis is used to identify and rank all possible cause/event combinations that might occur in the gun compartment which could lead to an undesirable result such as a fire or explosion. In the gun compartment, the hazards are usually situations wherein a specific set of circumstances (or events) can occur in a specific order, with the overall result (or final event) subjecting the aircrew or aircraft to a high degree of risk of bodily injury, death, damage, or destruction of the aircraft. Gun compartment hazard analysis can be performed on existing aircraft to assess their relative safety. However, it is more effective to initiate the hazard analysis at the conceptual design phase and continue the analysis through the production and testing phases. Initiation of a hazard analysis at the earliest possible stage in an aircraft development cycle reduces the overall design costs by eliminating the need for expensive safety improvement retrofits, and by maximizing overall system performance by designing safety into the system, rather than being forced to accept retrofitted safety features that might overly restrict performance. This Design Note (DN) illustrates the effectiveness and advantages of initiating the gun compartment hazard analysis at the earliest possible stage and continuing it as the program develops, working with the safety and survivability sectors to insure an integrated, consistent approach. A typical diagram of the hazard analysis relationship to other analyses is shown in Figure A-1.

2. SITUATIONAL EXAMPLE

The need for gun compartment hazard analysis can be demonstrated by the description of an actual aircraft accident/incident. A round was improperly fed to the gun breech, causing the case to become lodged such that it would not extract. Because the first projectile did not properly extract, the second projectile caused a double feed. The double feed caused the gun to fire out of battery with three separate results (1) the gun bolt was damaged; (2) the aircraft was damaged; and (3) the mission was aborted. The damage to the gun bolt caused the gun to jam. The gun jam and the aircraft damage contributed to the mission abort. These cause/event relationships are known as the cascade effect. A diagram of this can be found in Figure A-2. As can be seen, many events can be both a cause and a result. Also, one cause may produce several results, or several produce the same result. A detailed hazard analysis, combined with other appropriate data, would identify these and other relationships to provide a means of identifying and verifying the most likely undesirable occurrences.

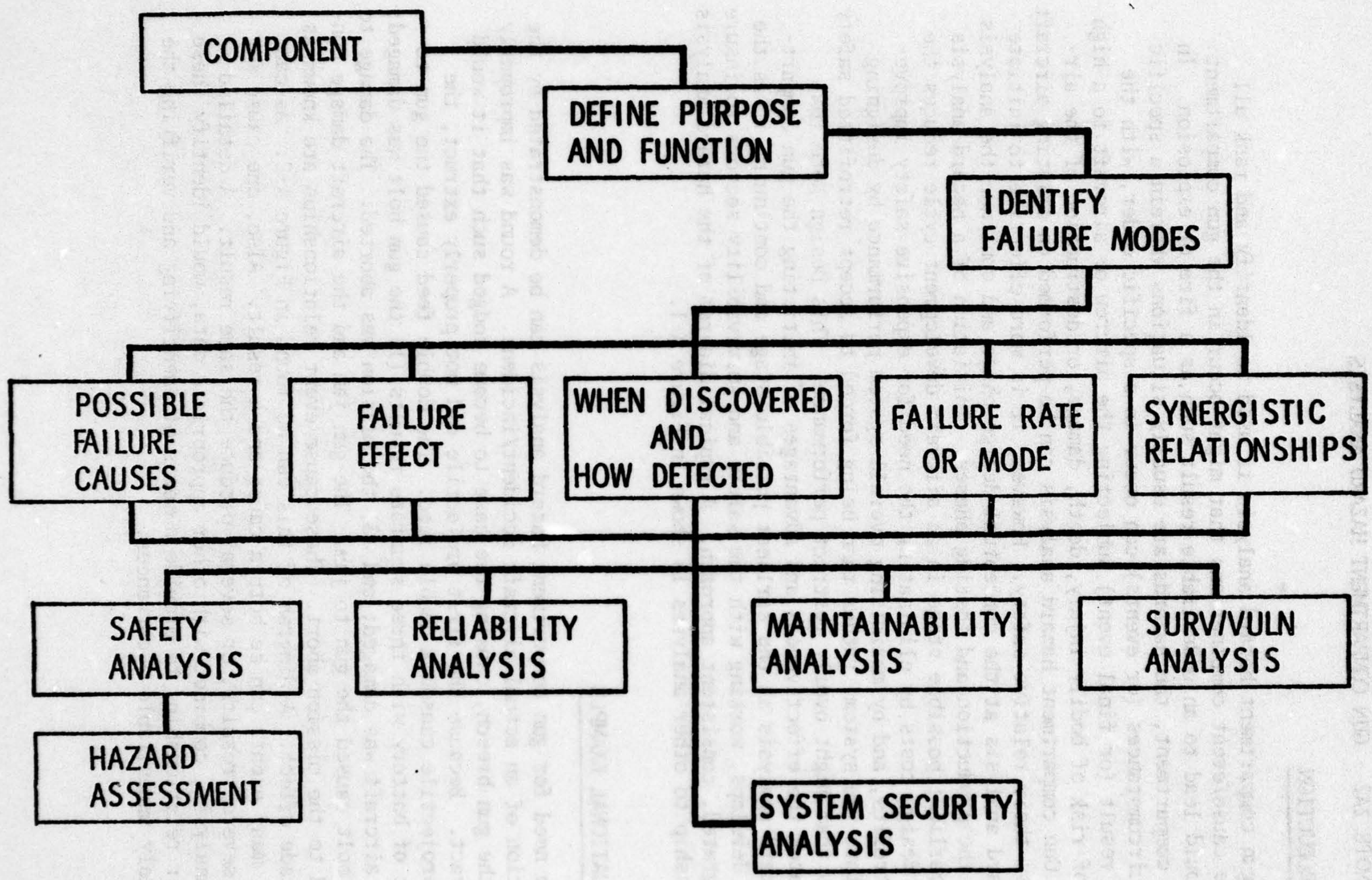


Figure A-1. Hazard relationship.

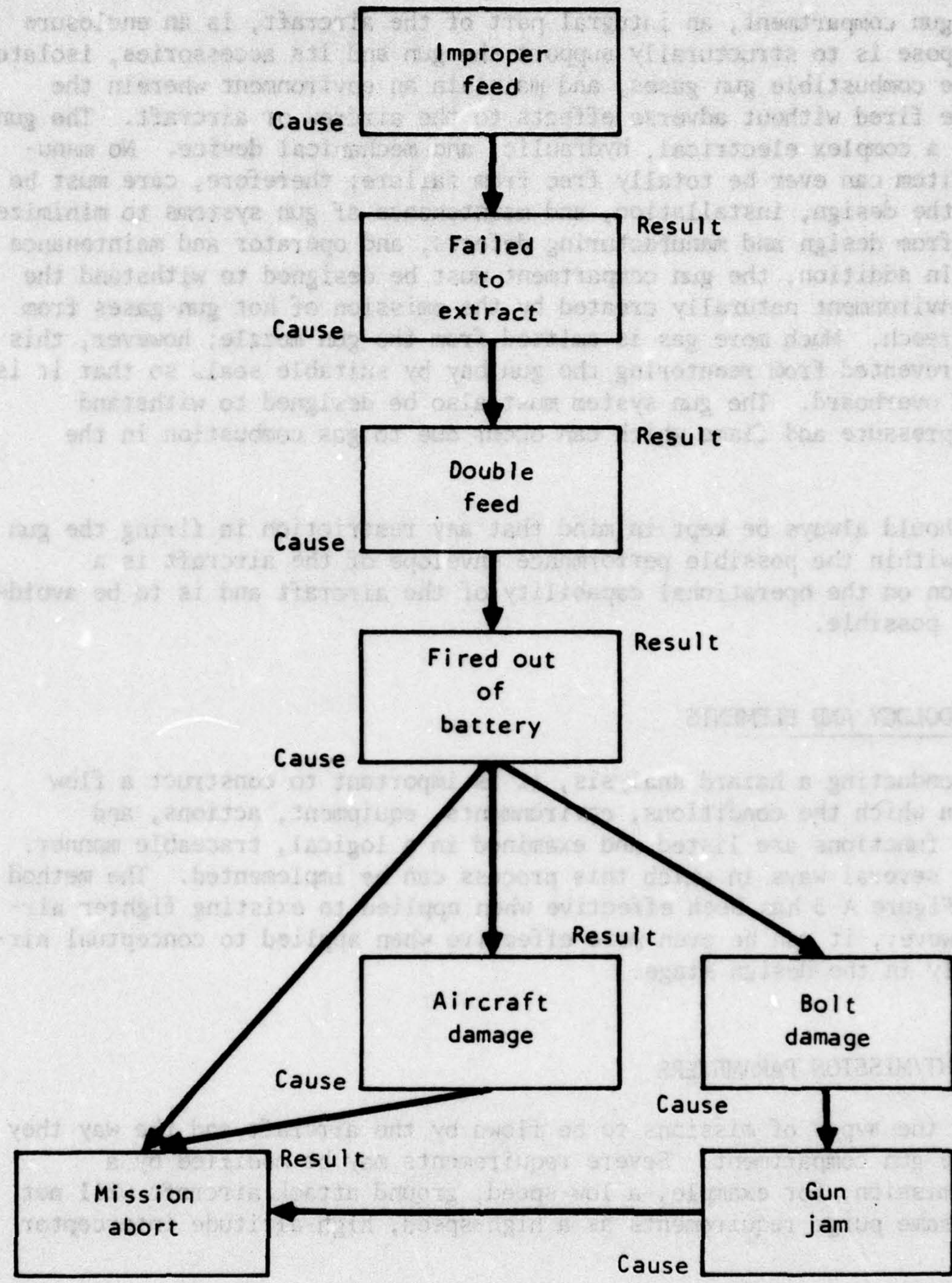


Figure A-2. Cascade effect.

3. OPERATIONAL ASPECTS

The gun compartment, an integral part of the aircraft, is an enclosure whose purpose is to structurally support the gun and its accessories, isolate and remove combustible gun gases, and maintain an environment wherein the gun can be fired without adverse effects to the aircrew or aircraft. The gun system is a complex electrical, hydraulic, and mechanical device. No manufactured item can ever be totally free from failure; therefore, care must be taken in the design, installation, and maintenance of gun systems to minimize failures from design and manufacturing defects, and operator and maintenance errors. In addition, the gun compartment must be designed to withstand the hostile environment naturally created by the emission of hot gun-gases from the gun breech. Much more gas is emitted from the gun muzzle; however, this must be prevented from reentering the gun bay by suitable seals so that it is exhausted overboard. The gun system must also be designed to withstand mild overpressure and flame which can occur due to gas combustion in the gun bay.

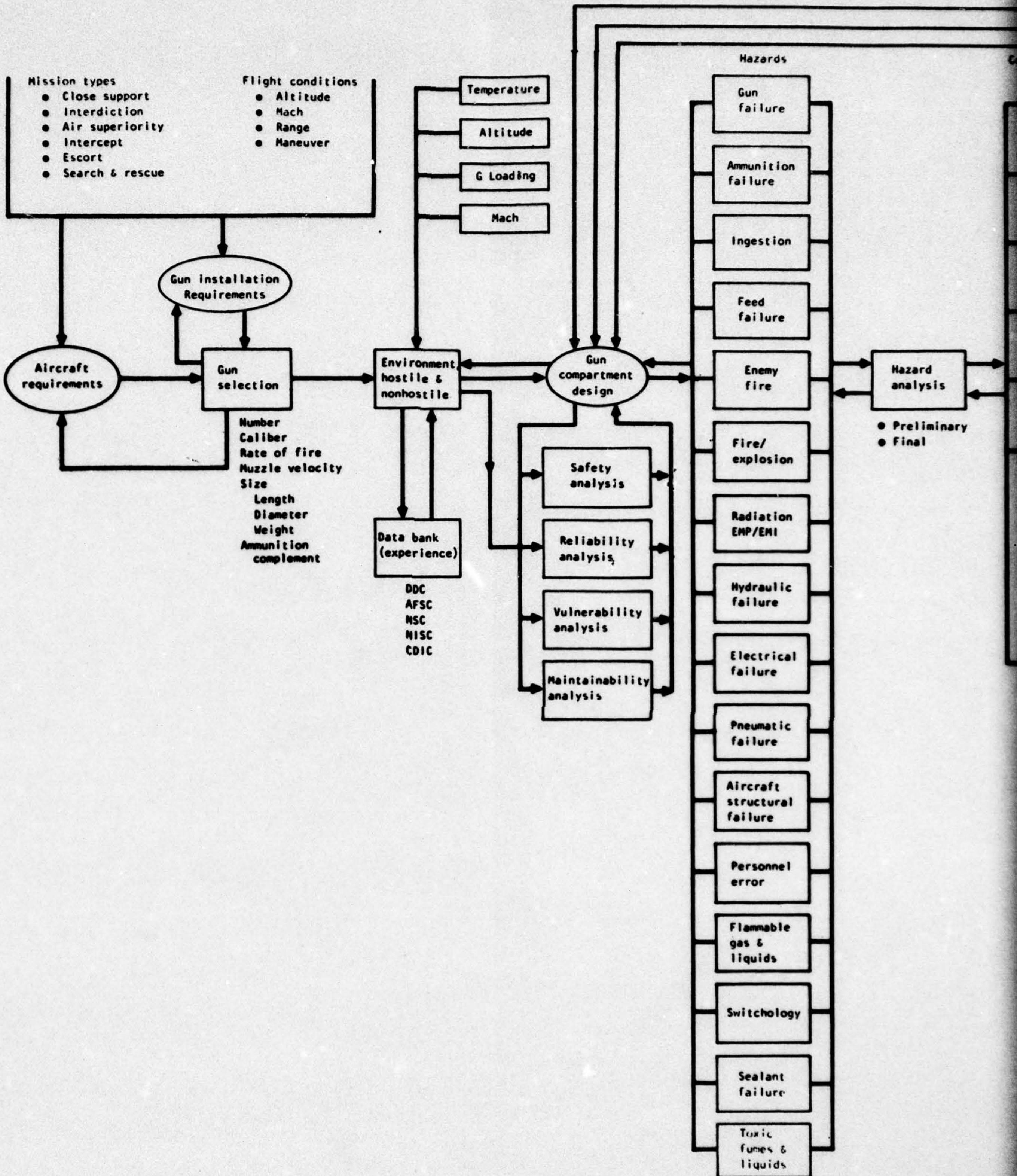
It should always be kept in mind that any restriction in firing the gun anywhere within the possible performance envelope of the aircraft is a restriction on the operational capability of the aircraft and is to be avoided if at all possible.

4. METHODOLOGY AND ELEMENTS

In conducting a hazard analysis, it is important to construct a flow diagram in which the conditions, environments, equipment, actions, and causative functions are listed and examined in a logical, traceable manner. There are several ways in which this process can be implemented. The method shown in Figure A-3 has been effective when applied to existing fighter aircraft; however, it can be even more effective when applied to conceptual aircraft early in the design stage.

4.1 FLIGHT/MISSION PARAMETERS

List the types of missions to be flown by the aircraft and the way they affect the gun compartment. Severe requirements may be modified by a selected mission; for example, a low-speed, ground attack aircraft will not have the same purge requirements as a high-speed, high-altitude interceptor type.



Mission types
Close support
Interdiction
Air superiority
Intercept
Escort
Search & rescue
Flight conditions
Altitude
Mach
Range
Maneuver
Gun installation Requirements
Aircraft requirements
Gun selection
Number
Caliber
Rate of fire
Muzzle velocity
Size
Length
Diameter
Weight
Ammunition complement
Temperature
Altitude
G Loading
Mach
Environment, hostile & nonhostile
Data bank (experience)
DDC
AFSC
NSC
NISC
CDIC
Gun compartment design
Safety analysis
Reliability analysis
Vulnerability analysis
Maintainability analysis
Hazards
Gun failure
Ammunition failure
Ingestion
Feed failure
Enemy fire
Fire/ explosion
Radiation EMP/EMI
Hydraulic failure
Electrical failure
Pneumatic failure
Aircraft structural failure
Personnel error
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Switchology
Sealant failure
Toxic fumes & liquids
Hazard analysis
Preliminary
Final

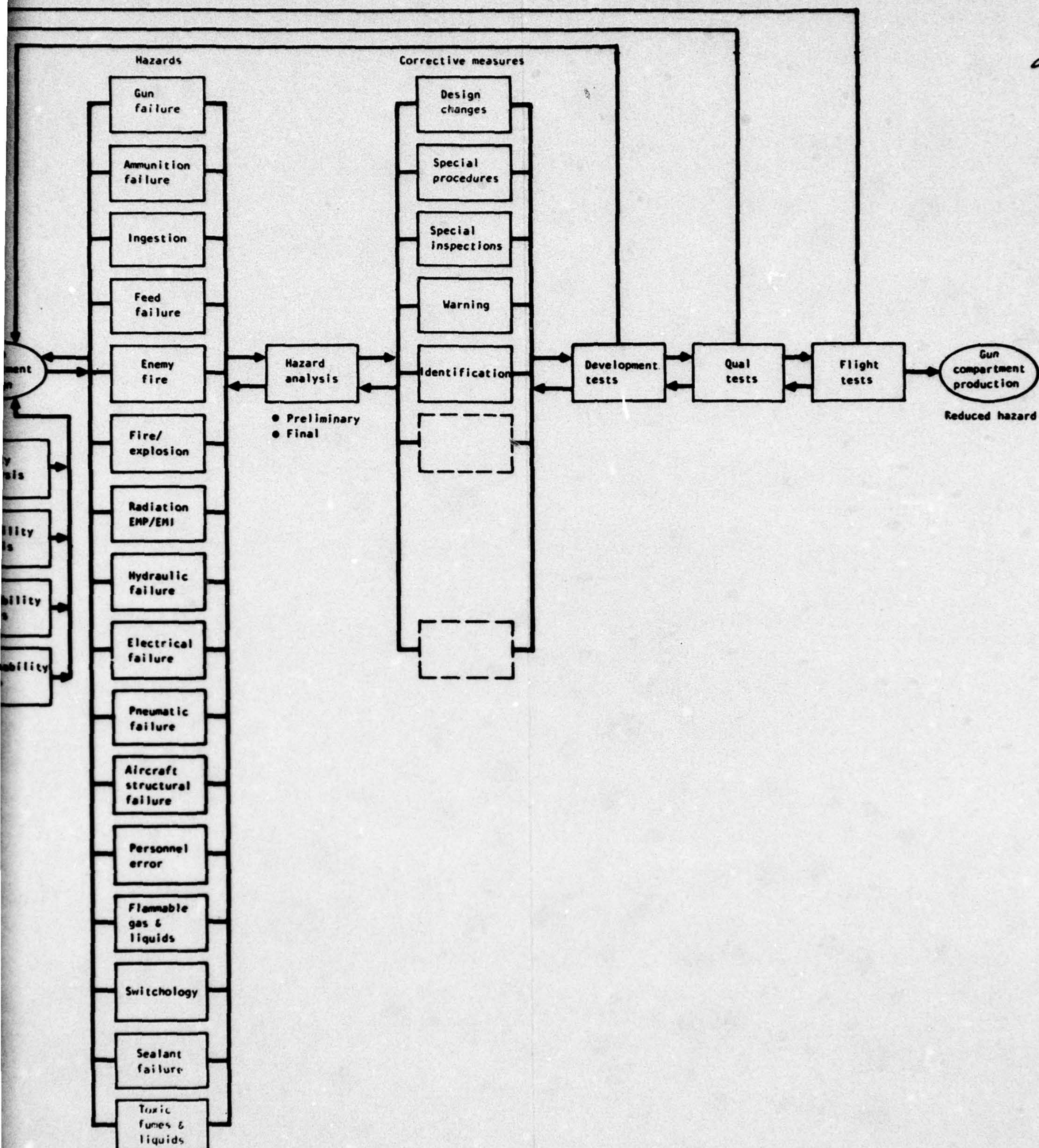

Figure A-3. Hazard analysis flow diagram.

4.2 HAZARD FORCES/ENVIRONMENT

Define the forces that act on the gun compartment and the environment in which the compartment will operate. Include personnel actions and similar controllable forces, along with the essentially uncontrollable forces such as altitude, temperature, speed, and "g" loadings.

4.3 HAZARD CONDITION DATA

Identify the hazard conditions by examination of the configuration and the equipment of the specific aircraft to be evaluated. Consider the data collected and evaluated on similar systems previously designed and operated. Contractors should consult their procuring agency for assistance in obtaining documentation of previous hazard analysis and operational experience.

4.4 PRELIMINARY HAZARD ASSESSMENT

Conduct a preliminary assessment as early in the conceptual design stage as is feasible. At this time basic criteria such as gun compartment size and shape, purge inlet and outlet, and proximity to other systems are being established. Consider the location of the guns and ammunition to fuel lines, hydraulic and pneumatic lines, crew compartment, and fuel tanks.

Review the statistical data on failures and consider the consequences should they occur early in the design process; provide protective measures where feasible; and update periodically as the design evolves.

Consider the effect of a gun jam, the most frequent accident historically, in which all the moving parts in the gun and feed system may come to a sudden stop with attendant material failure. Consider the effect of an explosion from a double-fed round, or a hang fire in which the round has emerged from the gun and may be as far as the storage drum on the return side before it explodes. Consider the effect of a round fired out of sequence so that the firing barrel is in other than the firing position. Consider the effect of gun or feed system structural failure in which broken parts may be expelled with high velocity. Consider the effect of gun-gas combustion throughout the bay during gun firing.

4.5 SAFETY ENHANCEMENT STUDIES

Consult the system safety functions and assure that a preliminary safety plan is prepared. Conduct a continuous dialogue between the armament design team and the system safety team so that safety considerations are an early part of the design effort.

4.6 SAFETY/SURVIVABILITY ENHANCEMENT TECHNIQUES

Consider techniques which can improve the safety evaluation results and reduce the hazards or reduce the possible results emanating from the hazards. Evaluate alternate design methods, select different components, or protect potentially vulnerable areas, for example.

Enhancement techniques that can reduce the potential hazards and improve safety and survival include:

1. Redundancy/separation/isolation
2. Damage tolerance
3. Delayed failure
4. Leakage suppression and control
5. Fire and explosion suppression
6. Fail-safe response
7. Masking/armor/geometry

4.7 TRADE STUDIES

Conduct trade studies to qualify and justify alternate techniques for safety enhancement. Evaluate the different methods in terms of weight, volume, cost, maintainability, and reliability.

4.8 DETAILED HAZARD ASSESSMENT

As the design effort moves from the early conceptual design to the prototype detail design, hazard analysis and system safety considerations will be included in accordance with those defined in MIL-STD-882. Conduct additional trade studies to quantify the improvements. Repeat the process in greater detail as production design is accomplished.

4.9 VALIDATION TESTING CRITERIA

Review each test phase to verify that the system is in compliance with the hazard analysis, and that the test results confirm the analysis. This includes development tests, ground tests, and flight tests. Change the

hazard analysis in accord with configuration changes made and the hazards found during testing. Review the hazard analyses to insure that they are consistent with the gun compartment, as built and tested.

Establish criteria for the individual test phases in accordance with the Prime Item Specification, and the applicable MIL specifications. Verify that the hazard analysis is consistent with specified system requirements.

DESIGN HANDBOOK DH 2-5

ARMAMENT

CHAPTER 3, MUNITIONS

SECTION 3E, GUNS AND AMMUNITION

DESIGN NOTE 3E2, HAZARDOUS CONDITIONS DATA

DRAFT/OUTLINE OF PROPOSED SECTION

CHAPTER 3 MUNITIONS

Section 3E Guns and Ammunition

Design Note 3E2 - Hazardous Conditions Data

1. Introduction

2. Gun Gases

   2.1 Gas Composition

   2.2 Flammability Limits

   2.3 Design Procedure

3. Flammable Materials

   3.1 Hydraulic Fluids

   3.2 Fuels

   3.3 Lubricants

   3.4 Oxygen

4. Ignition Sources

   4.1 Guns

   4.2 Electrical

   4.3 Hostile Threats

   4.4 Ammunition Cookoff

5. Detection Techniques

6. Lessons Learned

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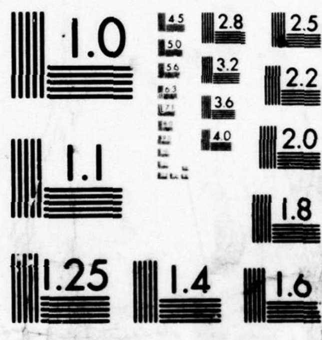

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Design Note 3E3 - Safety Enhancement Techniques

1. Introduction
2. Hazard Factors and Severity Values
3. Safety Enhancement Techniques
    3.1 General
    3.2 Gun Failure
    3.3 Ammunition Failure
    3.4 Personnel Actions
    3.5 Feed Failure
    3.6 Purge Failure
    3.7 Aircraft Structural Failure
    3.8 Hydraulic/Pneumatic System Failure
    3.9 Excessive Burst Length
    3.10 Sealant Failure
    3.11 Gun Shroud Failure
4. Fire Detection/Extinguishing
5. Gun Compartment Geometry
6. Ammunition Storage

Design Note 3E4 - Validation Testing Criteria

1. Introduction
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1. INTRODUCTION

Consider the conditions that exist in aircraft gun compartments due to the necessity of firing high-performance guns and the manner in which the components and materials can be combined to hold potential hazards to acceptable limits. A thorough knowledge of the gun and its operating characteristics is essential. Respect for the amount of energy transfer during gun firing is needed. Keep in mind that the M-61A1 gun delivers 23,000 horsepower (hp) when it fires at 6,000 shots per minute (spm). Design to prevent combustion of gun-gases within the bay if possible, but use materials with structural and flame-resistant properties adequate to resist combustion if it occurs. Identify and characterize potential ignition sources.

2. GUN-GASES

Gun-gas, which is the gaseous product of the combustion of solid propellant within the cartridge case, is potentially the most serious fire and explosion hazard within the gun compartment. This effluent leaves the gun at the muzzle and at the breech. Design the muzzle seal to prevent the entry of gas around the barrel and into the bay. Locate the muzzle exit from the aircraft so that the gas will not blow back into purge inlets, engine inlets, or other fuselage openings. This will confine the gas problem to the breech effluent which is much less than the muzzle effluent. Gun-gas, when sufficiently concentrated and mixed in proper proportions with air and ignited, can seriously damage or destroy the aircraft. The problem is not as severe as altitude increases and at compartment altitudes above 45,000 feet, test data show that ignition cannot occur.

2.1 GAS COMPOSITION

Combustion of gun propellants in a high-pressure (50,000 psi) gun chamber produces a gas composition which can be accurately predicted using free-energy thermodynamic equilibrium calculations. Expansion and cooling of these gases, however, do not follow the thermodynamic equilibrium predictions because of chemical kinetics considerations. The predominant reaction taking place during the expansion and cooling process is the water-gas reaction (Equation 1)

$$CO + H_2O \rightleftarrows CO_2 + H_2 \tag{1}$$

A series of calculations was made, using equilibrium constant data available in the JANNAF thermochemical handbooks, to establish the concentrations of the water-gas reactants (CO, H_2O, CO_2, and H_2) at various temperatures, from gun propellant combustion temperature 2,300° to 300° K. These results indicate that there would be a significant shift in gas composition between the high- and low-temperature regions.

$$K = \frac{(CO_2 + x)\ (H_2 + x)}{(CO - x)\ (H_2O - x)} \tag{2}$$

where

K = equilibrium constant

$(CO_2 + x)$ = mole fraction of CO_2 etc

x = fraction disassociated

However, experimental data on combustion of explosives obtained by Bernecker and Smith (Reference 1) indicate that the water-gas reaction will not proceed as predicted by equilibrium constant calculations.

Instead, their data, based upon chemical analysis of the gases produced by combustion of various explosives, indicate that the water-gas reaction effectively ceases if rapid cooling of the combustion products occurs. Their samples were burned in a standard 240-ml Parr high-pressure bomb with the gases contained within the bomb and allowed to cool by heat transfer to the bomb body. The gases produced during combustion of explosives (cyclo-tetramethylene tetranitramine (HMX), cyclonite (RDX), cyclotol (COMP B), and pentaerythritol tetranitrate (PETN)) are very similar to the gases produced by solid gun-propellant combustion; therefore, their data should be directly applicable. The cooling rate of the gun-gas free-expansion should be at least as fast as the closed chamber (Parr bomb) tests of Bernecker and Smith.

As a conservative estimate, therefore, using the methods described in Reference 1, the "freezeout" temperature is expected to be near 1,700° K. Consequently, the gun-gas composition predicted at 1,700° K in the water-gas reaction calculations is the best estimate of the actual gas composition in the gun compartment. This composition is only slightly different from the gas composition in the gun chamber, as shown in Table A-1.

TABLE A-1. GUN-GAS COMPOSITION

Propellant	Gas Composition, Mole Percent						
	H_2	H_2O	CO	CO_2	CH_4	N_2	Misc
Rocketdyne Gun Propellant (RGP) - future GAU-8 applicability							
Chamber (2,024° K)	26.3	14.5	26.5	3.2	1.5	27.4	0.6
Freezeout (1,700° K)	27.0	13.8	25.8	3.9	1.5	27.4	.6
Canadian Industries Ltd. (CIL) - GAU-8 applicability							
Chamber (2,264° K)	16.7	16.6	47.0	8.6	.1	10.8	.2
Freezeout (1,700° K)	18.6	14.7	45.1	10.5	.1	10.8	.2
Olin - M-61A1 applicability							
Chamber (2,241° K)	17.0	17.6	45.8	8.9	.2	10.4	.1
Freezeout (1,700° K)	18.9	15.7	43.9	10.8	.2	10.4	.1

2.2 FLAMMABILITY LIMITS

Any combustible gas or vapor when mixed in the proper proportion with air is capable of producing combustion on being ignited. If small increments of combustible gas are successively mixed with air, a composition will be reached at which the mixture just becomes combustible. The concentration of combustible gas at this composition is referred to as the lower flammability limit (LFL) and represents the minimum concentration of the particular combustible gas or vapor in mixture with air that will propagate flame if ignited. If the concentration of combustible in this mixture is progressively increased, a composition will be reached at which the mixture again becomes noncombustible. The concentration of combustible in the mixture just before this point is reached is known as the upper flammability limit (UFL) and represents the maximum concentration of the particular combustible gas or vapor in mixture with air, that will propagate flame if ignited. All compositions between the upper and lower limits are within "the flammable range" and are flammable. All compositions of mixtures containing less combustible than the lower flammability limit concentration and more than the upper limit concentration are nonflammable by themselves.

As will be shown later, inert gases such as carbon dioxide and nitrogen, have the property not only of depressing or narrowing the flammable range of any combustible gas or vapor, but also of preventing the formation of flammable mixtures when these inert gases are mixed in suitable proportions either with the air, or with the combustible gas, or with a flammable mixture of both. (Reference 2.)

The flammability components of the gases resulting from the combustion of common gun propellants are hydrogen, carbon monoxide, and methane. These gases have flammability limits in air as listed in Table A-2.

Mixtures of gases may also have flammable limits which are defined by the LeChatelier relationship,

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \text{----} = 1$$

in which N_1, N_2, N_3, etc, are the lower (or upper) limits in air for each combustible gas separately and n_1, n_2, n_3, etc, are the percentages of each of the gases in any lower (or upper) limit mixture in air. While this relationship has been found not to be universally applicable, it gives reasonably accurate results for mixtures of the combustibles in gun gas; i.e., hydrogen, methane, and carbon monoxide.

TABLE A-2. LIMITS OF FLAMMABILITY OF GUN-GAS CONSTITUENTS

Gas	Formula	Limits of* Flammability	
		Lower	Upper
Hydrogen	H_2	4.0	74.2
Methane	CH_4	5.0	15.0
Carbon monoxide	CO	12.5	74.2

*Volume % in air at atmospheric conditions

As an example and using only the three gases of Table A-2 and their respective lower limits with the Olin propellant of Table A-1:

$$\frac{n_1}{4.0} + \frac{n_2}{5.0} + \frac{n_3}{12.5} = 1$$

$$(H_2) \quad (CH_4) \quad (CO)$$

and knowing the volume ratio of the three gases to be added to air, say 30.0% H_2, 0.3% CH_4, and 69.7% CO, we find that:

$$n_2 = 0.01\, n_1$$

$$n_3 = 2.32\, n_1$$

We can solve for n_1, n_2, and n_3 and determine that a mixture of

2.29% H_2 (volume)

0.023% CH_4 (volume)

5.30% CO (volume)

92.39% Air (volume)

100.00%

is at the lower flammability limit and that 7.61% (volume) of the three gas mixture in air is at the LFL.

The Bureau of Mines, in one of the earliest investigations of the flammability of mixtures of combustible gases (Reference 3), measured the flammability limits of gases from mine fires, mine explosions, detonation products of explosives, and other gases of similar character: i.e., mixtures of CH_4, CO, and H_2. The test data were then compared with calculated results using the LeChatelier relationship.

Close agreement between the calculated and experimental results for many gases examined validates the use of LeChatelier's relationship for mixtures of the gases.

A more useful formula, derived through a transformation of the basic LeChatelier rule, is, from the foregoing example:

$$L = \frac{100}{\frac{p_{H_2}}{N_{H_2}} + \frac{p_{CH_4}}{N_{CH_4}} + \frac{p_{CO}}{N_{CO}}}$$

$$L = \frac{100}{\frac{30}{4} + \frac{0.3}{5} + \frac{69.7}{12.5}} = 7.61\%$$

in which L is the limit (lower or upper) of a mixture of combustible gases, and p_{H_2}, p_{CH_4}, and p_{CO} are the proportions (volume) percent of hydrogen, methane, and carbon monoxide present in the original mixture, so that:

$$p_{H_2} + p_{CH_4} + p_{CO} = 100$$

or

$$30 + 0.3 + 69.7 = 100\%$$

If the original mixture contains small amounts of air or inert gases (less than 10%), this relationship may be applied without introducing an error of more than 10% in the calculated limits.

When the total volume percent of air and/or inert gases in the original mixture exceeds 10%, the following procedure should be used.

Limits of Original Mixtures Containing Large Amounts of Air and/or Inert Gases

An extension of the law to apply to original mixtures containing large amounts of air and/or inert gases is that, when limit mixtures are mixed, the result is a limit mixture, provided that all constituent mixtures are of the same type; that is, all are lower limit mixtures (lean) or all are upper

upper limit mixtures (rich). The following procedure therefore may be used to calculate the limits of flammability:

Step 1. The composition of the original mixture is first recalculated on an air-free basis; the amount of each gas is expressed as a percentage of the total air-free mixture.

Step 2. A somewhat arbitrary dissection of the air-free mixture is made into simpler mixtures, each of which contains only one flammable gas and part or all of the nitrogen or carbon dioxide.

Step 3. The limits of each mixture thus dissected are read from tables or curves. (See Figure A-4.)

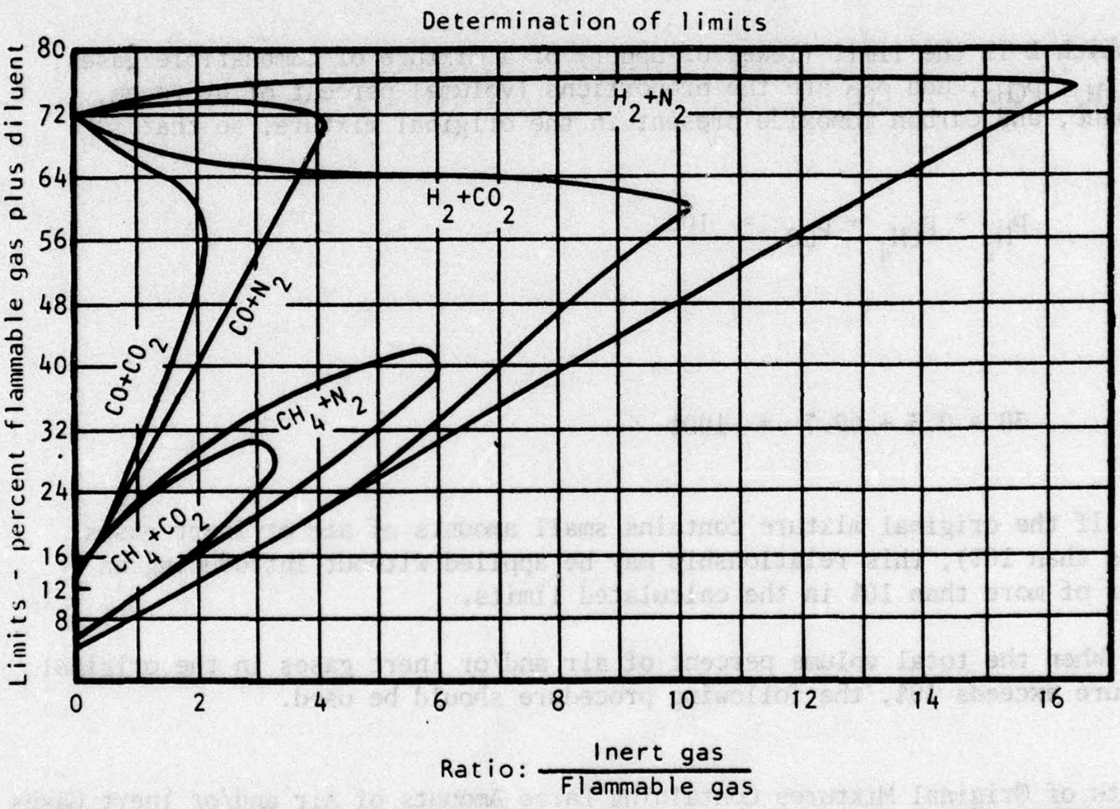


Figure A-4. Limits of flammability of hydrogen, carbon monoxide, and methane containing various amounts of carbon dioxide and nitrogen.

Step 4. The limits of the air-free mixture are calculated from the figures for the dissected mixtures obtained in step 3, by means of the equation:

$$L = \frac{100}{\frac{p_1}{N_1} + \frac{p_2}{N_2} + \frac{p_3}{N_3} + \cdots},$$

where p_1, p_2, p_3 . . . are the proportions of the dissected mixtures, in percentages, and N_1, N_2, and N_3 . . . are their respective limits.

Step 5. From the limits of the air-free complex mixture thus obtained, the limits of the original complex mixture are deduced.

The following is an example of the calculation applied to the Olin freezeout composition in Table A-1.

H_2 - 18.9%
CO - 43.9
CH_4 - 0.2
CO_2 - 10.8
H_2O - 15.7
N_2 - 10.5

100%

1. Since this is already an air-free mixture, step 1 is omitted and the flammable gases are paired off with the inert gases separately to give a series of dissected mixtures, as shown in Table A-3. Some discrimination is needed to choose appropriate quantities, but a fair latitude of choice is usually available.

2. The limits of the dissected mixtures, from Figure A-4, are shown in the last two aforementioned columns. For example, the first mixture contains 43.9 percent of carbon monoxide and 7 percent of nitrogen; the ratio between its nitrogen and carbon monoxide is 7/43.9 = 0.16; and the limits from the curve for carbon monoxide - nitrogen mixtures are 13-percent (lower) and 72.5-percent (higher).

TABLE A-3. SERIES OF DISSECTED GAS MIXTURES

Component	Percent		CO_2	N_2	Total Percent	Ratio I/C	Limit (From Fig. A-4)	
							Lower	Upper
CO	43.9		–	7	50.9	0.16	13	72.5
H_2	18.9	9.9	–	11.4	21.3	1.15	8.5	73.5
		9.0	18.2	–	27.2	2.02	12.5	66
CH_4	0.2		0.4	–	0.6	2.0	17.5	28
Total	63.0		18.6	18.4	100.0	–	–	–

I/C = Ratio of inert to combustible gases

NOTE: This example assumes the water vapor to be 7.8% CO_2 and 7.9% N_2. This assumption will be documented later.

3. The values in the last two columns and in the column "total percent," substituted in the equation, give the two limits of the air-free complex mixture, calculated to 0.5 percent:

$$\text{Lower limit} = \frac{100}{\frac{50.9}{13} + \frac{21.3}{8.5} + \frac{27.2}{12.5} + \frac{0.6}{17.5}} = 11.6\%$$

$$\text{Upper limit} = \frac{100}{\frac{50.9}{72.5} + \frac{21.3}{73.5} + \frac{27.2}{66} + \frac{0.6}{28}} = 70\%$$

Since the original complex mixture did not contain air, the flammability range is therefore 11.6 to 70 volume percent. If, for example, the original

mixture had contained air (say 13.4 volume percent), the original mixture lower limit would be:

$$\frac{11.6 \times 100}{(100-13.4)} = 13.39\%$$

The upper limit would be:

$$\frac{70 \times 100}{(100-13.4)} = 80.83\%$$

The chief complication with such calculations is in choosing the appropriate amount of inert gas to pair with each combustible gas. The ratio of inert to flammable gas must not be so high that the mixture falls outside the extreme right of the corresponding curve in Figure A-4.

In addition to the gases for which data are given, the gas in the example contains water. Little data exist on the effectiveness of water as an inerting substance for a mixture of combustible gases. However, Coward and Gleadall, Reference 4, showed that the effect of water vapor as an inert gas on the explosibility of methane is intermediate between that of CO_2 and of N_2. *Assuming that the effect on hydrogen and carbon monoxide would be similar to* that on methane, it seems reasonable to divide the water vapor proportionally between the carbon dioxide and nitrogen and increase the quantities of those gases accordingly. Thus, since the amounts of carbon dioxide and nitrogen in the gun-gas are approximately equal (10.8- and 10.5-percent, respectively), the water was divided equally (to the nearest 0.1 percent) and the portions added to the two inert gases. The total adjusted percentages become CO_2, 18.6 percent, and N_2, 18.4 percent. To check the sensitivity of the limit calculations to the distribution of the water, limits were determined for a case in which all the water was added to the CO_2 and for one in which the water was added to the N_2. Results for all cases are compared in Table A-4 and the corresponding limits are listed in Table A-5.

Following the procedure just described, the lower and upper flammability limits for the three gun-gas compositions shown in Table A-1 composition were computed for the freezeout condition. Results are shown in Table A-6.

TABLE A-4. GUN-GAS FLOW RATE

	Component		Percent	CO_2	N_2	Total Percent	Ratio I/C	LFL	UFL
$H_2O\begin{pmatrix}7.8\ CO_2\\7.9\ N_2\end{pmatrix}$	CO		43.9	-	7	50.9	0.16	13	72.5
	H_2	18.9	9.9	-	11.4	21.3	1.15	8.5	74
			9.0	18.2	-	27.2	2.02	12.5	66
	CH_4		0.2	0.4	-	0.6	2.00	17.5	20
	Total		63.0	18.6	18.4	100.0	-	-	-
$H_2O(15.7+CO_2)$	CO		43.9	-	7	50.9	0.16	13	72.5
	H_2	18.9	9.9	-	3.5	13.4	0.35	6	72.5
			9.0	26.1	-	35.1	2.90	16	65.0
	CH_4		0.2	0.4	-	0.6	2.0	17.5	28
	Total		63.0	26.5	10.5	100.0	-	-	-
$H_2O(15.7+N_2)$	CO		43.9	-	7	50.9	0.16	13	72.5
	H_2	18.9	9.9	-	19.2	29.1	1.94	12.5	74.5
			9.0	10.4	-	19.4	1.16	9	68
	CH_4		0.2	0.4	-	0.60	2.0	17.5	28
	Total		63.0	10.8	26.2	100.0	-	-	-

TABLE A-5. EFFECT OF WATER VAPOR DISTRIBUTION

Water Vapor Allocation (Percent)		Flammability Limit (Percent)	
N_2	CO_2	Lower	Upper
50	50	11.6	70.4
-	100	11.9	69.4
100	-	11.9	71.7

TABLE A-6. LIMITS OF FLAMMABILITY OF GUN-GAS MIXTURES

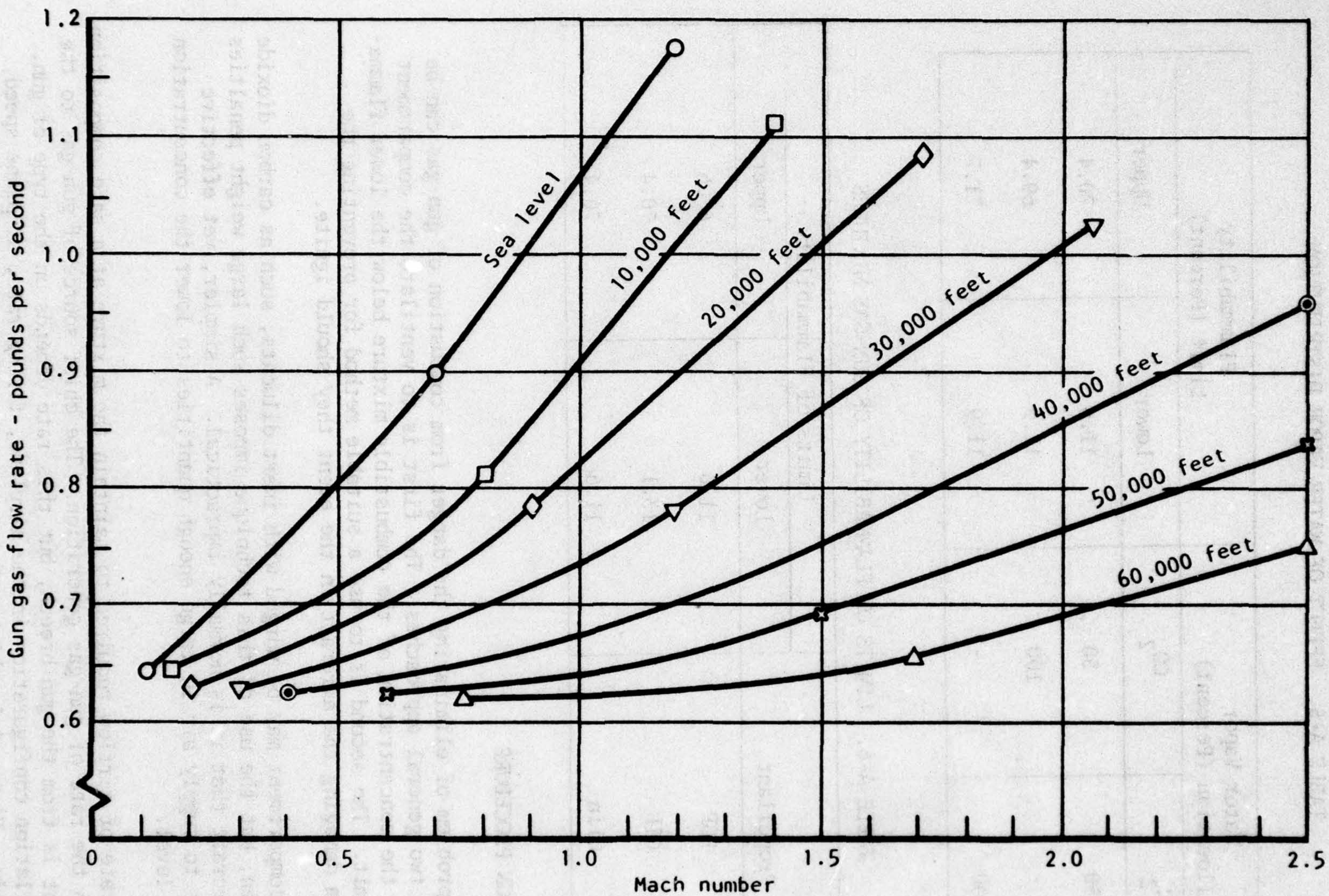
Propellant	Limits of Flammability	
	Lower	Upper
RGP	11.6	67.6
CIL	13.1	70.4
Olin	11.6	70.4

2.3 DESIGN PROCEDURE

The problem of eliminating the danger from combustion of gun-gas can be solved by two general approaches. The first is to ventilate the compartment to reduce the concentration of the combustible mixture below the lower flammability limit. The second is to use a suitable method for preventing the gases from damaging the aircraft in the event they should ignite.

The compartment may be purged with inert diluents, such as carbon dioxide or nitrogen, but the use of this technique imposes such large weight penalties on the aircraft that it is normally impractical. A simpler, yet effective method, is to supply air in large enough quantities to lower the concentration to a safe level.

The rate of airflow required to maintain the mixture at a safe composition depends on the rate of gun-gas generation. The chief source of gun-gas to the compartment is from the gun breech, but this rate depends on the type of gun, its installation configuration in the airplane, firing rate, airplane speed, and altitude. Figure A-5, which was developed by McDonnell Douglas as part of



Courtesy McDonnell Douglas Corp

Figure A-5. Total gun gasflow rate (muzzle and breech flow).

its F-15 effort, is a family of representative curves showing the gun-gas flow rate from the breech for the M-61A gun mounted in the F-15. The data include the effect of gases which are blown back through the barrel. Thus, at a mach number of 0.9 at sea level, in this gun-airplane combination, 1 pound of gun-gas per second would flow into the gun compartment.

To evaluate the difficulty of maintaining a low gun-gas concentration by purging a gun compartment with air, the amount of air needed to keep the concentration at 100-percent LFL was computed. For Olin propellant, the LFL of a mixture of gun-gas and air is 11.6 percent. That is, a mixture of 11.6-percent gun-gas and 88.4-percent air is a lower limit mixture, or 100-percent LFL. The percentage by weight of the constituents of a gaseous mixture may be determined from the molar compositions by multiplying their corresponding molar percentages by the molecular weights to obtain the weights per mole of the mixture, and then dividing by the total of the weights per mole which is the equivalent weight of the mixture. The procedure is summarized in Table A-7 for the gun-gas.

Using the same procedure on a mixture of 11.6-percent gun-gas and 88.4-percent air by volume (100-percent LFL), the weight ratios are obtained as shown in Table A-8.

TABLE A-7. OLIN GUN-GAS COMPOSITION

Component	Percent by Volume	Pound/ Mole	Pound/ Mole Mix	Percent by Weight
H_2	18.9	2	0.378	1.62
CO	43.9	28	12.292	52.94
CH_4	0.2	16	0.032	0.14
CO_2	10.8	44	4.752	20.47
H_2O	15.7	18	2.826	12.17
N_2	10.5	28	2.940	12.66
Total	100.0	--	23.220	100.00
Mole weight of mix (gun-gas) = 23.22 pounds per mole.				

TABLE A-8. 100-PERCENT LFL COMPOSITION

Component	Percent by Volume	Pound/ Mole	Pound/ Mole Mix	Percent by Weight
Gun-gas	11.6	23.22	2.694	9.52
Air	88.4	28.97	25.609	90.48
Total	100.0	-	28.303	100.00

Thus, the mass flow of air (assuming perfect mixing) to obtain a lower limit mixture (100-percent LFL) would be:

$$W \text{ air} = \frac{\text{Percent air by wt}}{\text{Percent gun-gas by wt}} \times \text{rate of gun-gas generation}$$

$$= \frac{90.48}{9.52} (1) = 9.50 \text{ pounds air/second}$$

This corresponds, in round numbers, to a volume of air at 14.7 psia and 70° F (which has a density of 0.075 pound per cubic feet) of

$$V \text{ air} = \frac{9.5}{0.075} (60) = 7{,}600 \text{ cfm}$$

In most cases, practical considerations will preclude supplying air at such a high-flow rate. At higher altitudes, because of the lower air density, an even higher flow rate would be indicated. However, in general, "reduction in pressure below 760 mm generally narrows the range of flammability by raising the lower limit and decreasing the higher limit" (Reference 5). The impact of this phenomenon on the gun-gas problem was therefore investigated.

Effect of Altitude on Flammability

At altitudes normally associated with aircraft, there is little change in the LFL, but as altitude increases, the probability of ignition at the LFL is reduced. Nevertheless, since a wide range of ignition sources is possible in a gun compartment, this altitude effect should not be the primary design criterion.

Theoretical calculations using chemical heats of combustion for constant volume (closed cylinder) burning of the fuels used in References 8 and 15 and of gun-gas were made. The results of such a series of calculations for sea-level initial conditions are:

Fuel	Calculated Pressure (psig)
40 percent hydrogen and air	130
1.15 percent JP4 vapor and air (100 percent sea-level LFL)	117
35 percent gun-gas and air (308 percent sea-level LFL--stoichiometric	112
5 percent propane and air	107
11.5 percent gun-gas and air (100 percent sea-level (LFL)	50

Using these figures as a guide and the experimental data of Reference 8. Figure A-6 was prepared to show how constituents and vent ratio (the ratio of the exit area to the volume of the combustion chamber) affect the combustion pressure developed. The estimated curves for gun-gas, of course, are not precise. However, the quantitative error cannot be appreciable since their relationship to the experimental curves must be in the order of the calculated zero vent ratio points and since the limits defined by the experimental curves are rather narrow. The curves show the significant effect of vent ratio in reducing the pressure rise associated with combustion. The stoichiometric gun-gas curve represents the upper limit of possible combustion pressure for gun-gas. Any lesser concentration would be deficient in fuel and any greater would be deficient in oxygen.

For a specific fuel-air mixture in a constant volume (zero vent ratio) combustion process, the final pressure attained depends mainly on the initial pressure. In a constant pressure (infinite vent ratio) process, the final pressure is the initial pressure. Therefore, for any vented chamber which falls between these two extremes, the final pressure is also mainly a function of the starting pressure. This reasoning allows the graph of Figure A-6 to be converted to the form shown in Figure A-7, where the ordinate is combustion-pressure ratio.

At vent ratios greater than 5, the reduction in maximum combustion pressure is negligible. Thus, for a vent ratio of 5 and using the Figure A-6 intersections of 100-percent sea-level LFL and for stoichiometric concentrations, the maximum obtainable pressure was determined as a function of altitude. Results are shown in Figure A-8. It may be seen that a chamber designed to

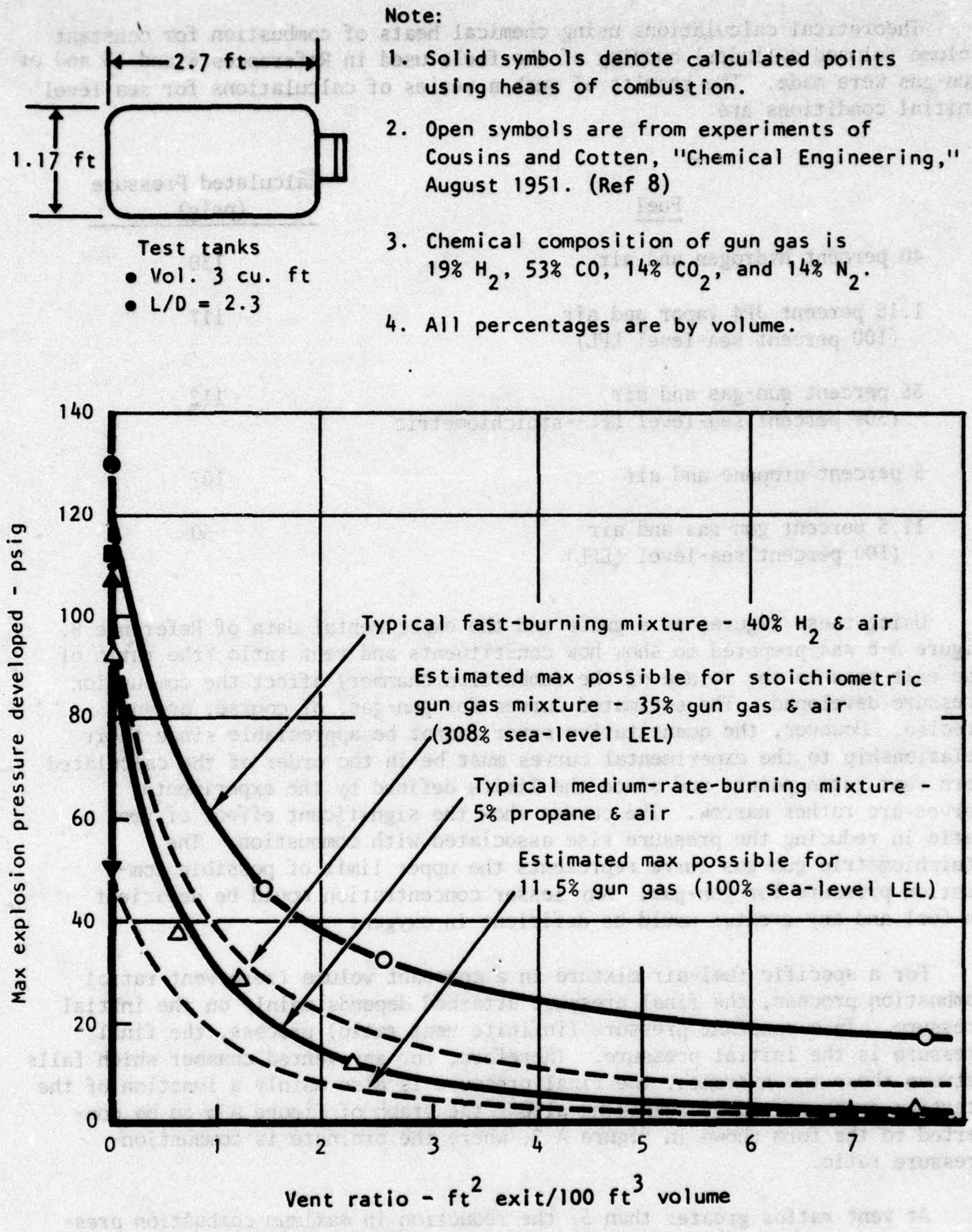
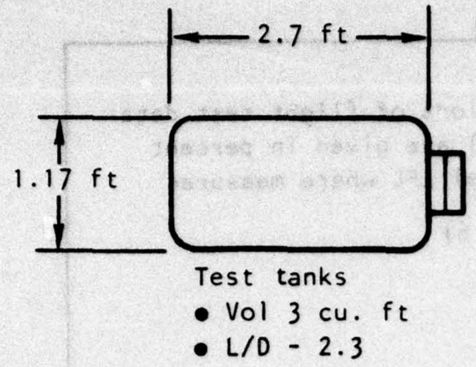


Figure A-6. Sea-level explosion pressures.



Note:
1. Solid symbols denote calculated points using heats of combustion.
2. Open symbols are from experiments of Cousins and Cotten, "Chemical Engineering," August 1951. (Reference 8)
3. Chemical composition of gun gas is 19% H_2, 53% CO, 14% CO_2, and 14% N_2.
4. All percentages are by volume.

Reference 6

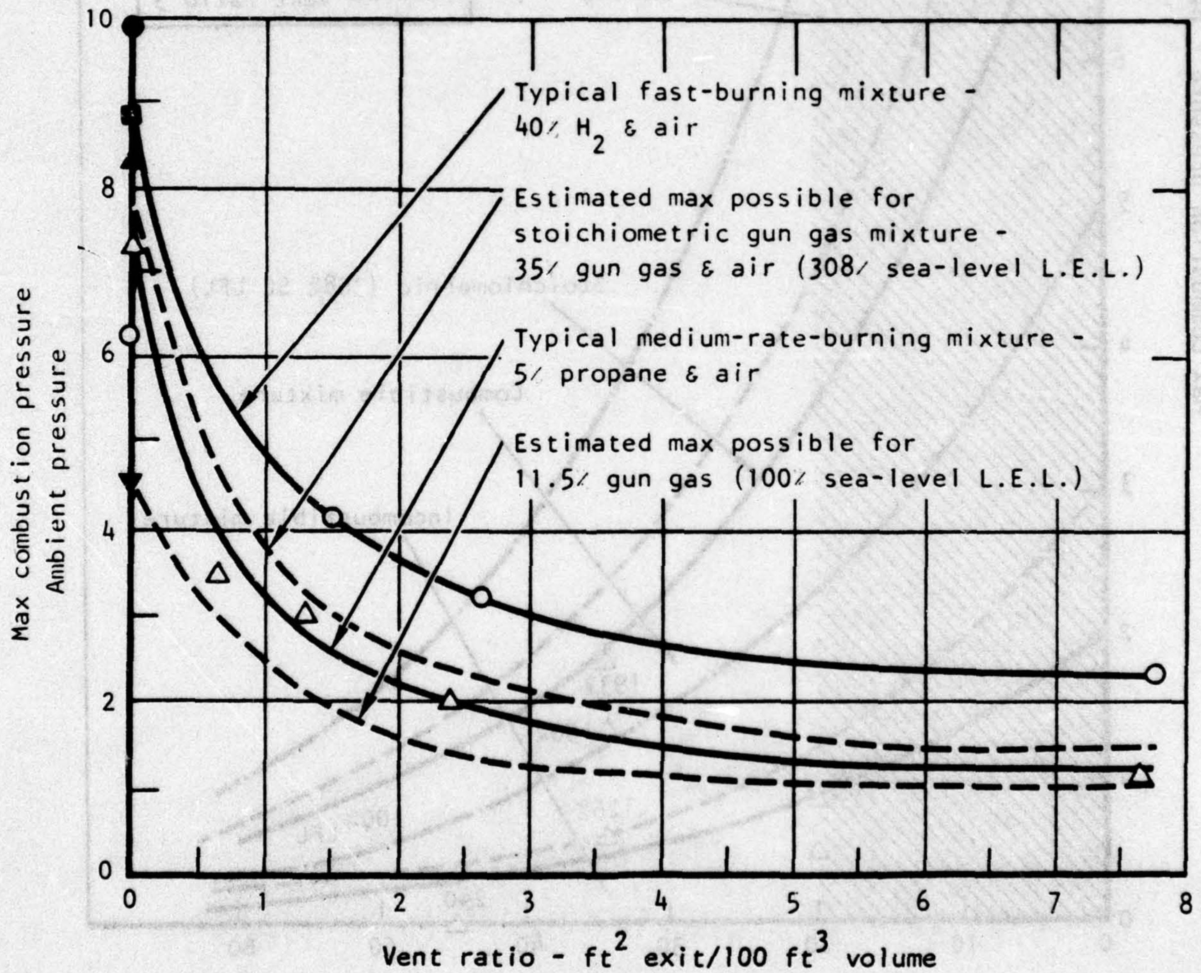


Figure A-7. Explosion pressure ratios from sea-level measurements.

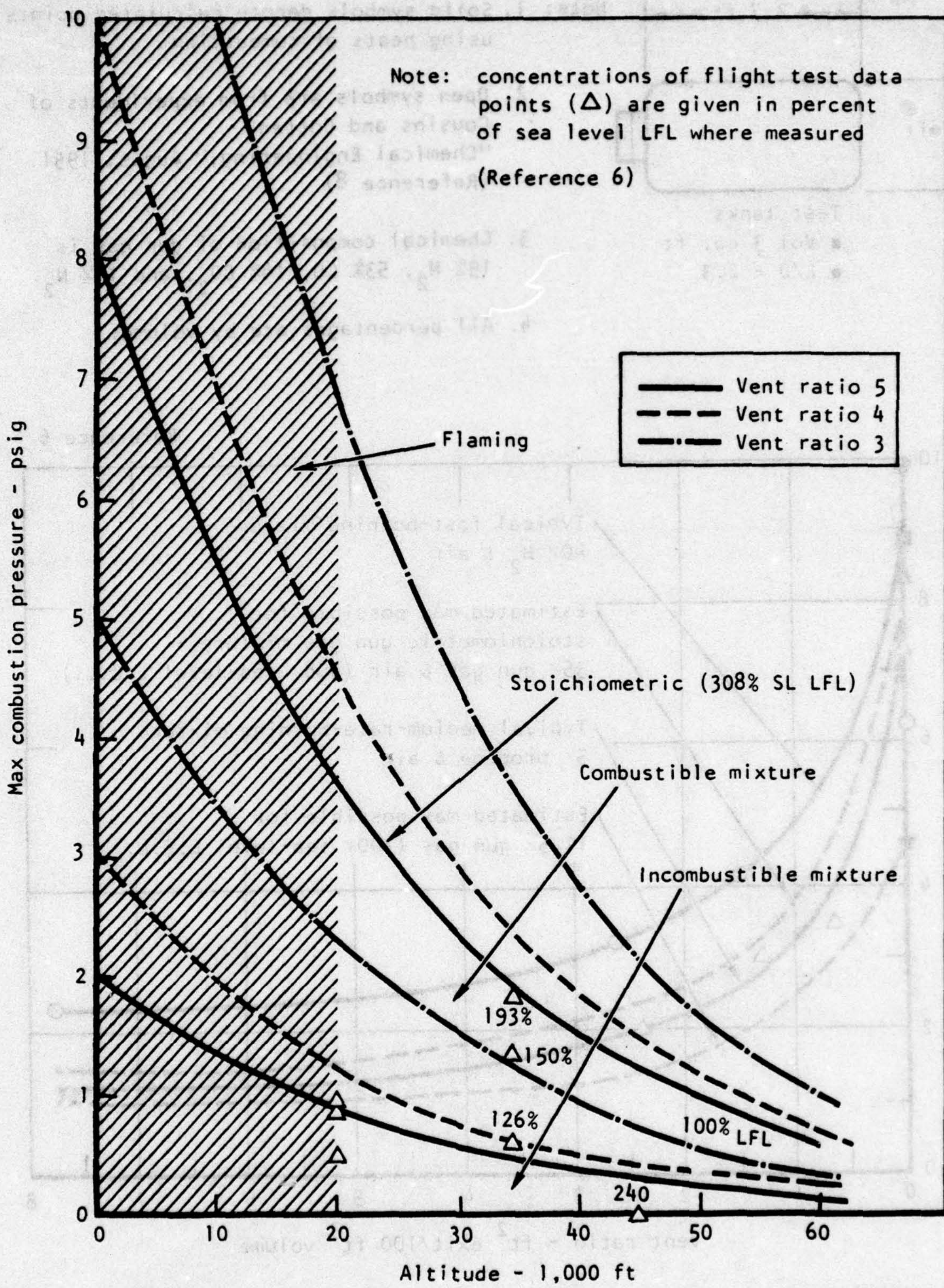


Figure A-8. Effect of altitude on combustion pressure for gun gas in a chamber with ratios of 3, 4, and 5.

withstand 2.5 psi bursting pressure would not be damaged by an explosion at sea-level of gun-gas in the 100-percent sea-level LFL concentration and that a chamber designed to 10 psi would withstand an explosion at sea-level of gun-gas in stoichiometric mixture with air. It should be noted further that fuel-rich mixtures (greater than stoichiometric) will produce pressures less than the stoichiometric curve, i.e., the stoichiometric curve represents a maximum limit. The effect of increasing altitude is to greatly reduce the maximum combustion pressure for a given mixture.

Considering, then, the area from 20,000 feet up, the data show that destructive pressures cannot result from burning of gun-gases in any concentration. This conclusion is born out by flight-test-measured pressures which have been noted in the figure. The average measured gas concentrations are indicated in percent of sea-level LFL for each point and it can be seen that the test points agree well with the theory as previously developed.

Similar curves for vent ratios of 3 and 4 are also plotted in Figure A-8 for comparison.

The theoretical data which has been previously discussed, refers to uniformly mixed specimens. Mixing in a gun bay, however, is far from uniform because of the irregular shape of most gun bays, location of equipment, non-uniform air and gas flows, and temperature variations. Therefore, a flame front, which might originate in one part of a gun bay, can be quenched by mixtures which are too rich or too lean.

Flammability characteristics in actual gun bays are not well known. Such data are usually obtained under laboratory conditions by igniting accurately measured compositions of gas and air in standardized vessels (tubes or closed shells). The size, shape, and material of these vessels can affect the measured combustion data in ways which could lead to erroneous conclusions when applied to gun compartments. Convective effects during laboratory measurements are minimal but, in a gun bay, very turbulent flows may exist. This turbulence, tending to improve mixing, should affect the flammability characteristics of the gun-gas/air mixture in a manner which cannot be predicted at present. Furthermore, because actual gun bays are less effective combustion chambers than test vessels because of irregular shapes, cold walls, non-homogeneous mixtures, and uncertain ignition, combustion in gun bays should be less hazardous than is indicated from basic combustion data. In the absence of definitive basic data concerning combustion under actual gun bay conditions, it appears that a practical approach to alleviating the combustion hazard is to purge the bay with air to the greatest feasible extent and to augment the purge with a design incorporating an adequate vent ratio (at least five). In addition, the gun bay structure should be designed to withstand overpressures of 5 psi or more for very short time intervals.

3. FLAMMABLE MATERIALS

The flammability of fluids which may be present in or adjacent to the gun compartment has been addressed in a number of studies and experiments. The ignition hazard level depends to a large degree on the ignition properties of the combustibles when exposed to different types of heat sources. These properties include behavior during ignition by electrical sparks or arcs, autoignition in uniformly heated containers, ignition by hot surfaces, and ignition by hot gases. Results of these studies were thoroughly documented in Reference 9.

The minimum autoignition temperatures are time dependent, and those shown in Table A-9 are based on maximum time delays. The high temperatures associated with the gun compartment are often of very short duration; accordingly, the autoignition temperatures may be correspondingly higher than those shown in Table A-9.

The AIT's are also significantly affected by ambient pressure and thus flight altitude. The AIT's of all the combustibles listed in Tables A-9 and A-10 are higher with increased altitude.

TABLE A-9. PROPERTIES OF HYDRAULIC FLUIDS (REF 9)

Fluid	Flash Point (° F)	Minimum AIT (° F)
Hydraulic Fluid		
MIL-H-5606C H-515 OHA (mineral oil)	195	437
MIL-H-83282 MLO-73-93	385	670
Chevron M2V MLO-71-45	208	698
MIL-2190 (mineral oil)	450	665
Mobil DTE 103 (mineral oil)	390	702
Cellulube 220 (phosphate ester)	455	1038
Harmony 44 (mineral oil)	460	680
Houghto-Safe 271 (water glycol)	—	767
Houghto-Safe 1055 (phosphate ester)	505	1020
Pydraul 150 (phosphate ester)	380	975
Pydraul AC (chlorinated ester)	450	1148
Skydrol (phosphate ester)	360	>1300

TABLE A-10. AVIATION FUEL FLAMMABILITY (REF 9)

Fuel	Flash Point (° F)	AIT in Air (° F)	Flamm Limits in Air LL Vol (%)	UL Vol (%)
JP-1	115	440	—	—
JP-3	—	460	1.4	7.9
JP-4	~ 0	445	1.3	8.0
JP-5	150	435	0.6	4.5
JP-6	100	450	0.7	4.8
JP-8	115	435	0.8	4.9
Jet A	105-140	435	Similar to JP-5	
Jet B	~ 0	450	Similar to JP-4	
Gasoline 100/130	-45	825	1.3	7.1
Kerosene	125	480	0.7	4.8

3.1 HYDRAULIC FLUIDS

Because power is used in conjunction with many armament systems, various hydraulic fluids may be present in gun compartments. The hydraulic fluid which is most commonly used in existing military aircraft is MIL-H-5606B hydraulic oil. Unfortunately, it has a low flash point, fire point, and auto ignition temperature, so a search for more fire-resistant fluids has been pursued for some time. The most promising ones are derived from mineral oils or are synthetic fluids such as phosphate esters. All have varying penalties in terms of cost, availability, special seal requirements, and impact on operational logistics, but their improved flammability characteristics make them attractive. Table A-9 contains a list of currently used fluids and promising ones which are under development.

In general, the vapor pressures of these materials are low; they are made up of high molecular weight materials because they are designed for use at elevated temperatures and pressures. However, they are flammable at ordinary temperatures and pressures as mists, and autoignition may occur if the residence or contact time is long enough. Even at atmospheric pressure, relatively low temperature could ignite a hydraulic fluid if enough vapor or mist is present. Since gas/air temperatures as high as 1,900° F (Reference 12) have been measured in gun compartments and barrel temperatures run as high as 1,000° F (Reference 10), igniting hydraulic fluid which might leak into the compartment is a distinct possibility.

3.2 FUELS

Jet fuels are extremely hazardous materials especially in the vicinity of potential ignition sources such as a hot gun barrel, spent shell cases, or breech exhaust gases. The lower flammability limit of JP-4, for example, is much lower than that of the gun-gases. Table A-10 lists flammability limits and AIT's for a number of jet fuels.

Under equilibrium conditions of fuel vapor/air concentration and temperature, the specification fuels have flammability limits which are temperature and altitude dependent. Figure A-9 compares JP-8 fuel and flammable mists with JP-4 fuel. It should be recognized that the data shown are only representative of typical fuels and that both the upper and lower flammability limits for individual fuels can vary within bands established by their specifications.

Thus, where fuel lines are routed through or near gun compartments, the possibility would always exist that fuel vapor or liquid could contribute to an unfavorable flammability situation. To minimize this problem, every effort should be made to keep these materials out of gun compartments.

3.3 LUBRICATING OILS

Table A-11 lists typical lubricating oils and their combustion properties.

3.4 OTHER MATERIALS

Other materials such as nylon, greases, aluminum, etc, which might be present in the gun compartment constitute little or no flammable hazard. If gun-gas or fuel were to be ignited, these materials could add fuel to the fire, but their effects would be small compared to the other sources.

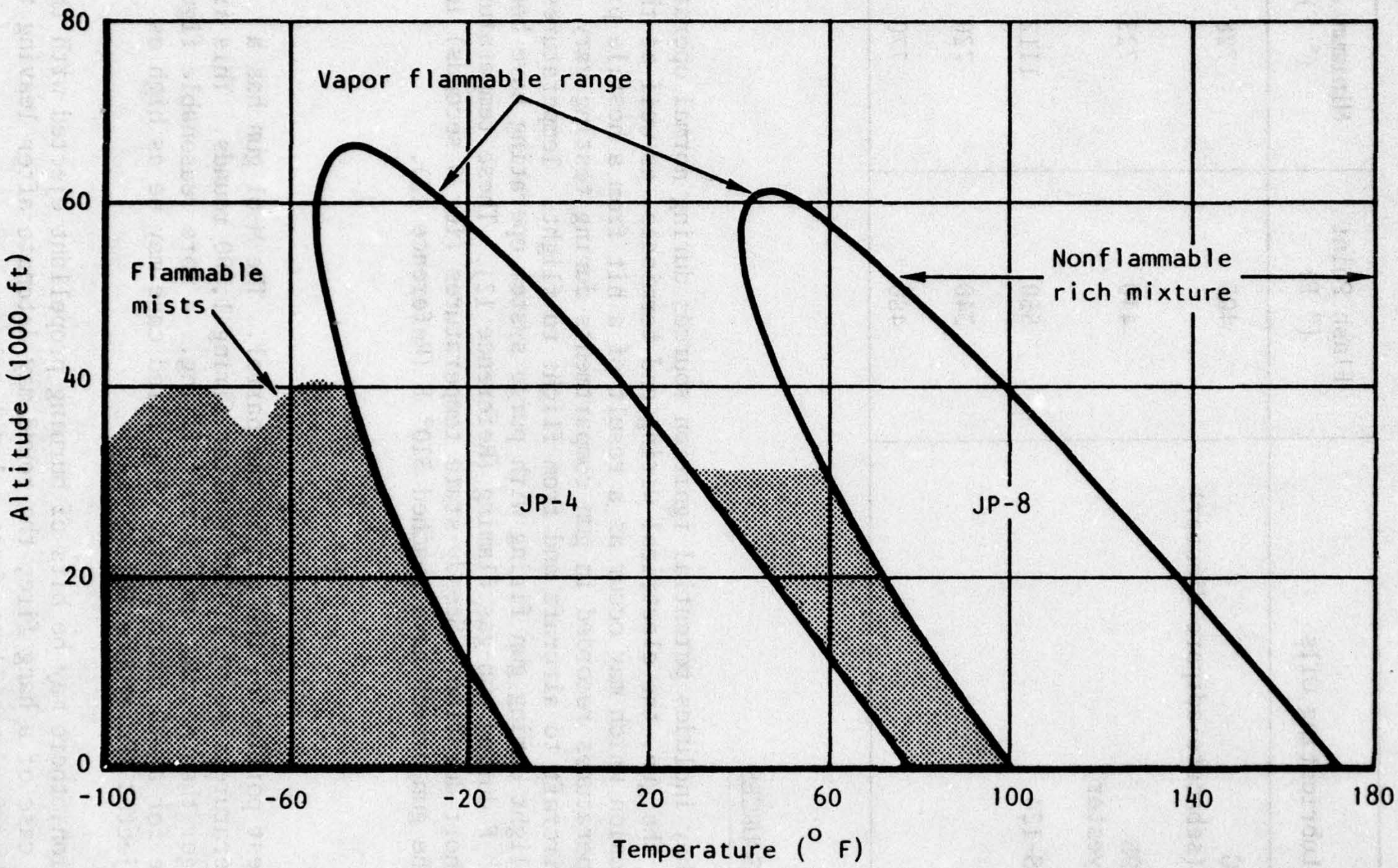


Figure A-9. Static flammability limits of fuels of different volatility (Reference 11).

TABLE A-11. PROPERTIES OF LUBRICATING OILS (REF 9)

Lubricating Oils	Flash Point (° F)	Minimum AIT (° F)
MIL-L-7808G O-148 LGT (sebacate-adipate diester)	405	728
MIL-L-23699B O-156 (polyester)	440	725
Monsanto OS-124	550	1112
SAE No. 10	340	720
SAE No. 60	480	770

4. IGNITION SOURCES

The gun bay includes potential ignition sources during normal operation; these include the gun, the electrical wiring and terminals, as well as the fire and explosion which may occur as a result of a hit from a hostile projectile. Temperatures recorded in gun compartments during testing vary widely from aircraft to aircraft and from flight to flight. Temperatures recorded in-flight during gun firing with purge system operating have been as high as 1,900° F during gun-gas flaming (Reference 12). These temperatures are of very short duration. Steady-state temperatures (for 6 seconds) in the vicinity of the gun breech have reached 310° F (Reference 13).

4.1 GUNS

The hottest portion of the gun is the barrel. The M-61 gun has a possible temperature rise of 1,000° F after firing 1,200 rounds. This is considerably longer than normal for aircraft firing. A more reasonable figure is 425° F-rise for a 300-round burst. The fired case may be as high as 400° F when ejected (Reference 10).

In addition, there may be bits of burning propellant ejected with the case. In the case of a hang fire, the round may detonate after leaving the gun, spewing burning propellant about a large volume.

4.2 ELECTRICAL

Under normal conditions, the possibility of an electrical arc which could ignite flammable material is small; however, lightning, structural failure, burned or frayed insulation, or improperly assembled connectors could provide the spark.

4.3 HOSTILE THREATS

Projectiles or shrapnel from enemy gun or missile fire are eminently capable of igniting flammable material within the gun bay.

4.4 AMMUNITION COOK OFF

Ammunition cookoff, in which a round explodes from excessive heat, normally occurs in a gun after long firing with attendant high gun chamber and barrel temperatures. However, high temperatures on the ammunition in the feed and storage system can also cause cookoff. In at least one case, improper operation of the purge and ECS system of an aircraft during ground maintenance did result in several rounds cooking off in the gun compartment.

The process is heavily time-dependent. Even after the cookoff temperature is reached, some time elapses before the round goes off. Normally, guns have an automatic clearing device to empty hot chambers at the end of firing. In case of a malfunction, it may not be possible to clear the gun and cookoff may occur.

Experiments conducted with the M-197 gun and the M56A3 20mm ammunition (Olin WC870 propellant) show that a burst of 348 rounds will induce cookoff in 2-4 minutes after the end of the burst. Propellant will cookoff after exposure to 360° F for 4 minutes (not substantiated by gunfiring tests) (Reference 14).

The M-61 20mm gun reaches ammunition cookoff temperature after firing approximately 480 rounds (assuming an initial barrel temperature of 75° F). This is based on test data (Reference 10).

5. DETECTION TECHNIQUES

There are two general methods of determining the gun-gas concentration in a gun compartment; i.e., the sampling bottle and the catalytic sensor. Each has procedures and requirements peculiar to its use and to the analysis of the results.

The sampling bottle is normally installed remote from the gun, and hence the source of the gas, to avoid damage during gun firing. A tube runs from the desired sampling point to the bottle. A solenoid-operated valve is provided so that the bottle may be evacuated prior to the test and the valve closed to hold the vacuum. At the desired sampling time, the valve may be electrically actuated for the desired interval whereupon a sample of the gas is drawn into the bottle. The valve is then closed. After the test, the bottle is removed and the contents analyzed by a mass spectrometer or a similar precise laboratory-type instrument. The Orsat-type analysis is commonly used to determine the percentages of the constituents and thus their flammability. The advantage of the bottle technique is that the analysis is very accurate if the system is pressure-tight and good instrumentation is employed. Disadvantages are that the bottle samples are at one specific interval, and installing and removing bottles at each test is time-consuming and may be physically difficult. When glass bottles are used they are easily broken. Also, the system must be pressure-tight to avoid contamination and to make sure that an adequate sample is captured during the brief time the bottle is open. Further, the time delay between sampling and laboratory analysis may induce a chemical change to the sampled constituents.

The catalytic sensor operates on the Wheatstone Bridge concept in which the gas is drawn in and burned in the presence of a catalyst so that change in electrical resistance provides a signal which is displayed in a remote unit. The system is calibrated before the test by circulating a certified gas through it. Normally, a sampling tube runs from the sensor to the sampling location, however, the sensor is small enough and rugged enough so that it could be placed closer to the sampling source than a fragile bottle. Circulation in the sampling tube is by means of a pump which draws the sampled gas through tube and sensor continuously as needed. The principal advantage to the catalytic sensor is its ability to provide a continuous reading in real-time. This provides a time history of the gaseous constituents. In addition, it is semipermanently installed and does not have to be removed for analysis after every sampling period. The disadvantages are (1) there is difficulty in accurate calibration (the calibrating gas must be accurate in the percentages of its constituents), (2) a sampling time lag could cause it to fail to respond to the initial gas concentration, and (3) there is the possibility that the sensing element can become saturated (catalytic poisoning) and give an erroneous reading. In addition, the readings may be affected by temperature and pressure (altitude).

Recently there have been efforts to develop sensors based on entirely different principles, however, these have not been placed on the market as of yet. Future gun-gas test requirements should stipulate a thorough review of sensor accuracy and availability before tests are begun.

6. LESSONS LEARNED

The possibility that a gun compartment-related accident will occur is statistically very small. In a modern, well-designed airplane, properly maintained, and correctly operated, the pilot can fire the guns, confident of accurate, reliable, and safe results.

The basic causes of accidents may be traced to such factors as definable deficiencies in training, supervision, attitude, and design. Within these broad categories, more detailed and descriptive causes may be found.

A study of accident records since 1962 showed a variety of detailed causes of the accidents that did occur. In Table A-12, these causes are listed in order of frequency of occurrence (1 is most frequent, etc). Degree of severity of eventual result is not considered here; however, all listed causes have the potential for causing fire and/or explosion in the aircraft.

TABLE A-12

Number	Factor
1	Gun
2	Ammunition
3	Personnel actions
4	Feed system

DESIGN NOTE 3E3 - SAFETY ENHANCEMENT TECHNIQUES

1. INTRODUCTION

This design note provides general techniques to enhance the safety of the gun installation in aircraft performance. Proper performance of aircraft gun systems depends on (1) the design of the gun system, (2) its installation in the aircraft, and (3) air vehicle and mission operational procedures during its service life. The considerations presented in this design note are by no means all-inclusive, but they indicate some of the most critical factors which effect safe operation of aircraft gun systems.

2. HAZARD FACTORS AND SEVERITY VALUES

Of the hazards identified under a study of hazard assessment of aircraft gun compartment, fire and/or explosion was the most critical. Twenty separate detailed causes for this hazard were found; however, many causes are amenable to alleviation by improved design or maintenance procedures. It is apparent that factors such as ammunition failure, enemy fire, gun structural failure, and personnel error cannot be controlled by aircraft design; but damage can be minimized by providing the proper environment and protection for the gun and ammunition.

While these causes also have high possibility of occurrence, they may be restrained by improved training, as well as better design, maintenance, and inspection procedures.

3. SAFETY ENHANCEMENT TECHNIQUES

The following discussion covers major hazards which have been identified in the operation of aircraft gun systems and suggests criteria for use in evaluation of system designs, with the objective of reducing or eliminating the possibility of occurrence.

Normally, critical components should be kept out of the gun bay. However, the operation of the gun itself may require potentially hazardous connections, such as electrical lines and connectors, and hydraulic lines for the gun drive. Further, the paucity of space in modern aircraft may require that other components (fuel lines, control lines, for example) also be placed within the bay. Early recognition of the hazards and prompt application of systematic safety techniques is essential. Consult DH1-6, System Safety Design Handbook for detailed treatment of this subject.

3.1 GENERAL

REDUNDANCY/SEPARATION/ISOLATION

Evaluate the use of duplicate or redundant systems to perform essential functions. Consider separation, or mutual masking of redundant systems to minimize or prevent failure or malfunction. For example, multiple control linkages provide redundant systems that permit the aircraft to function when one element has ceased to function after damage by impact, fire, or explosion. Remove the critical portions from areas of potential hazard.

DAMAGE TOLERANCE

Consider design techniques which will provide essential structure and components which will accept a degree of damage without impairing their capability to perform their functions. This may be accomplished by providing redundant load paths, high-fracture toughness material, large diameter and thin wall control rods, nonmetallic bell cranks and cable sectors, and high temperature tolerance features.

DELAYED FAILURE

The choice of construction or system operating media materials can have a significant influence in minimizing vulnerability. This consideration must be made early in the design effort, in order to take advantage of such benefits. For structural elements and subsystem components that must retain their load-carrying integrity, high fracture toughness materials should be selected. This is necessary to prevent or limit crack propagation following damage. Other considerations may be the selection of high-temperature-tolerant materials in areas where the component or structure may be exposed to fire or hot gas "torching."

LEAKAGE SUPPRESSION CONTROL

One of the most significant hazards is the liberation of flammable, toxic, or corrosive fluids that are used for the operation of military aircraft. There are two basic techniques that can be used to prevent or minimize dangerous consequences that can develop (1) leakage suppression, and (2) leakage control.

Leakage suppression is a technique that uses self-sealing materials designed to accept a degree of ballistic damage and seal the damaged area with

little or no leakage from the fluid container. This serves two basic purposes (1) the fluid is retained for its intended use, and (2) the liberation of the fluid to areas where fire, toxic products, smoke, or corrosive reactions may be generated that would endanger the crew or operation of essential subsystems is suppressed.

Leakage control is a technique that may be used to handle and direct liberated fluids or vapors in such a manner that danger to the aircraft and crew is minimized. This technique includes sealing of sensitive or ignition-producing area, drainage provisions, flow diverters, and venting features.

FAIL-SAFE RESPONSE

Once the vulnerable subsystems and their components have been identified, their response to gun bay damage effects must be analyzed. This analysis should consider methods of preventing or minimizing subsequent unsafe or hazardous conditions. This is the basic objective of fail-safe response techniques. This analysis may be integrated with reliability and system failure mode and effects analysis where similar factors are considered. The criteria for fail-safe response are similar for each of these specialties, with the major difference being the cause of initial failure. For survivability, it is the primary or secondary weapon effects; for reliability, it is material failure; and for safety, it is a nonhostile hazardous environment.

An example of fail-safe response is the incorporation of an electrical interlock between the purge entrance door and the gunfiring circuit so that in the event that the door does not open when the trigger is actuated, the gun will not fire. This will avoid possible dangerous accumulation of gun gas in the compartment caused by the gun firing without adequate purge air circulation.

Other examples of this technique include:

- The design of hydraulic accumulators that use high-pressure gas charging, with pressure-limiting valves or blowout plugs that will prevent explosive disintegration of the gas pressure section when exposed to fire or high temperatures.
- The design of essential gearboxes and bearings to operate for an extended period when loss of lubrication has been experienced.
- The design of multiple-load-path structure which provides fail-safe protection by preventing catastrophic failure when a load path is severed or severely damaged.

MASKING/ARMOR/GEOMETRY

The protection of aircraft personnel and flight/mission-essential components, when exposed to gun bay damage effects, is vital. Reduction of the effects of fire and explosion on the aircraft is a method to enhance survivability. This can be done by a combination of techniques, including natural masking, redundancy, separation, isolation, damage tolerance/resistance, leakage suppression, minimized detection, and the use of armor if still necessary. How these methods can be used, either independently or in combination, must be considered in the initial design effort in order to eliminate the need for, or to minimize the amount of armor required to supplement the other techniques.

NATURAL MASKING

The structure, consumables, and components of an aircraft system can act as a barrier for personnel or flight/mission-essential components against weapon effects. The technique of natural masking is to arrange those elements in a fashion to gain the most protection with the least penalties and to incorporate the protection with the rest of the design requirements. When using this technique, the designer must also consider the accessibility of the elements being masked. The gains in protection must be weighed against the time and effort required to maintain aircraft in both peacetime and combat operations to determine the most effective design configuration. Taking advantage of natural masking will minimize the amount of additional material or armor needed to defeat a specific hostile threat level.

ARMOR SYSTEMS

Ideally, armor should defeat projectiles or fragments before damage can be inflicted on the component that the armor has been designed to protect. The basic mechanisms for defeat are the projectile breakup and/or absorption of the kinetic energy of impact. All armor and armor systems use these or variations of these methods.

Criteria have been developed to measure the energy absorption and the weight effectiveness of armor material and systems compared to a standard material.

Armor materials may be used singly or in combination to form armor systems, or they may be used in the fabrication of the aircraft structure.

3.2 GUN FAILURE

Provide gun mounts that are structurally adequate to withstand forces and vibrations during prolonged firing. Use reliable locks and latches. A sizable number of incidents occur when the gun moves from its normal restraint. Consider that a double-feed or hang fire may cause the gun to fire when the barrel is not in the firing position (rotated past the firing sector). Consider that a gun structural failure may result in broken parts expelled with considerable velocity. Locate critical lines and components to avoid damage from such an event.

3.3 AMMUNITION FAILURE

Be aware that ammunition failure is responsible for many accident/incidents in the gun and ammunition bay. Long or short rounds, hang fire, inadequately crimped case, and bad primer are all capable of causing malfunctions which could end in catastrophic fire and explosion. Consider the effect of burning propellant spilling from a ruptured case. Consider the effect of a round exploding anywhere in the return system after leaving the gun. Consider the effect of a double-feed or failure to fire, such that the round fires in other than the firing position. Consider the effect of a jammed round anywhere in the transfer system where the entire gun and feed system is brought to a sudden, complete stop. Select materials and structure, and locate components in such a manner as to negate, insofar as possible, the damage from these events.

3.4 PERSONNEL ACTIONS

Design the system to remove the possibility of failure or accident due to personnel actions to the maximum extent possible. Provide action sequences in which the correct method is the only alternative. Consult the integrated logistics functions throughout the design-development process. Make sure required functions meet the labor grade capabilities expected during operations. Devise interlocks and go-no-go functions which will reduce the human error element.

3.5 FEED FAILURE

Consider use of temperature-stable materials. Specify tighter dimensional tolerances during manufacture of components. Strive for rigid system designs with flexibility only at junction of moving parts. Specify stringent inspection and maintenance procedures. Emphasize reliability and strength of latching mechanisms. Avoid sharp bends and twists that can overstress flexible chuting. Ensure that remote drive mechanisms have adequate means of synchronization.

3.6 PURGE FAILURE

Consider ram air as the primary source of purge air. The natural volume and velocity of the air surrounding the aircraft nose section offers vast flexibility in quantity of purge air. Provide a reliable and efficient air scoop system. Keep operating linkages and components simple to avoid failure to open or close at critical times. Design the power source for operation with adequate safety margin. Consider redundancy for reliability. Interlock purge door opening with trigger switch and gun-firing command to insure purge airflow before the gun starts to fire, and long enough after firing stops to remove all gas from the compartment. Use baffles or deflectors as necessary to route airflow throughout the bay, thus avoiding pockets of accumulated gas. Consider a fail-safe system design from a safety viewpoint, and a fail-operate design from an operational viewpoint.

Evaluate the need for a purge ejection system to scavenge gas at critical points. Secure an adequate source of air. Evaluate the comparative efficiency of ram air, engine bleed-air, or environmental control system air as an ejector source. Consider the effect on the aircraft of the demand for air during critical flight maneuvers. Design a reliable and efficient actuation system. Provide a means to prevent blow-back into the ECS system from combustion in the gun compartment. Consider redundancy for reliability. Interlock actuation system with the trigger switch and gun firing command to insure operation before the gun starts to fire, and long enough after firing stops to scavenge residual gas. Strive to exhaust gas overboard in a safe location. Consider a fail-safe design from a safety viewpoint, and a fail-operate design from an operational viewpoint. Keep ducting and valving simple and structurally adequate to withstand the flaming and overpressure from possible gas combustion.

Design for a vent ratio (square feet of exit area divided by 100 cubic feet of free bay volume) of at least five. Evaluate application of a variable louver system to increase airflow through the gun compartment under severe conditions. Provide for adequate airflow through the compartment during ground operation. Consider the use of blowout doors, relief panels, burst devices, or similar pressure relief means to protect the aircraft during unexpected overpressures.

3.7 AIRCRAFT STRUCTURAL FAILURE

Establish design criteria for gun compartment design which will consider maximum pressures and temperatures expected during normal gun operation, as well as the possibility of occurrence of unusual conditions (e.g., accidental discharge of ammunition, etc). Evaluate compartment configuration for dissipation of excessive overpressures. Appraise effectiveness of alternate materials. Eliminate or minimize use of flammable materials. Where such materials must be used, consider application of passive or active fire protection systems.

3.8 HYDRAULIC/PNEUMATIC SYSTEM FAILURE

Minimize routing of hydraulic/pneumatic lines within the gun compartment. Specify heavy lines or provide shielding. Avoid routing lines containing flammable fluids in the gun compartment. Provide a means to isolate damaged hydraulic/pneumatic lines from the rest of the system. Specify nonshattering bottles for pneumatic service.

3.9 EXCESSIVE BURST LENGTH

Excessive burst length could generate potentially dangerous temperatures and exhaust gas concentrations. Review inspection and maintenance procedures. Evaluate reliability of system components such as control valves and counters. Strive for a system that will permit firing of a full complement of ammunition without damage or failure.

3.10 SEALANT FAILURE

Evaluate application methods and materials used. Review inspection and maintenance procedures and consider revisions to improve them. Ascertain that a suitable vent ratio exists. Consider application of new sealant materials.

3.11 GUN SHROUD FAILURE

Review inspection and maintenance procedures. Consider use of improved materials and different design techniques. Use materials which will withstand shock and vibration of gun firing and which will withstand flame and high temperature for duration of firing.

4. FIRE DETECTION/SUPPRESSION

Consider the improvement in safety and reliability of providing a fire detection and/or suppression system in the gun bay, as opposed to the disadvantages due to the penalties in weight and volume, at least for prototype aircraft. If such a system is used, consider alternatives, including detection systems and suppression systems.

DETECTION

Consider visual- and heat-sensing systems for fire detection. Visual systems provide microsecond response to suppress combustion fronts, however,

gun flashes during firing could cause unwanted fire signals. If detector delays are designed into the system, consider the legnth and frequency of firing bursts. Heat-sensing devices may be either spot or averaging systems set to alarm when a predetermined temperature is reached. The setting can be set so as to ignore high temperature due to a long burst. These devices are not sensitive to gun flashes. They are, however, susceptible to vibration and connector moisture problems. These problems can be overcome by detail design.

SUPPRESSION

Consider the normal flight conditions affecting the gun compartment and the portion of the mission that the guns are operated.

Consider visual- and heat-sensing systems. Consider inerting systems which inject an inert fluid/gas into the compartment during and immediately after gun firing to preclude fire. Consider the weight penalty. Many of these systems require high maintenance and servicing after each gun firing. Some fluids are corrosive and require compartment flushing after each use.

5. GUN COMPARTMENT DESIGN

The aircraft configuration and the selected gun and ammunition complement will strongly influence gun compartment geometry and free volume. Within these limitations, design a compartment that will have adequate volume and purge air exit area to provide the desired vent ratio. Design the compartment structure to withstand overpressure due to possible gun-gas combustion and ram air. Provide paths for air circulation. Eliminate from the bay all components not essential to servicing and firing the guns. Provide adequate protection for adjacent compartments, especially fuel tanks and crew compartments.

ISOLATION

Separate the gun compartment from the rest of the aircraft with pressure walls that are sealed and drained. If fuel tanks are adjacent to the gun compartment, provide a double-wall structure between tank and compartment. Consider the pressurization of the gun compartment due to heating plus the pressure induced by the gun when it is fired.

VIBRATION AND ACOUSTICS

Gun firing induces vibration in the mounts, structure, equipment, fluid systems, ventilation systems, and adjacent compartments. Gun firing also induces acoustic levels that could damage the contents of the compartment, adjacent equipment, and personnel. Develop design criteria for compartment structure and internal equipment to tolerate vibration and acoustic levels. Consider the effects on structure, seals, and drains for both compartment and equipment. Consider the movement of compartment walls in double-wall construction as the compartment wall responds to gun vibration and acoustics.

SEALING

Seal the compartment walls that separate the gun compartment from the remainder of the aircraft. Use flexible seals to allow structure flexibility due to pressure changes without loss of sealing capability. Select seals that can withstand the changes in the environment of the compartment. These changes include (1) sudden pressure changes; (2) ambient-to-maximum pressure at both maximum temperature and minimum temperature; and (3) exposure to fuels, hydraulic fluids, water, solvents, and gun gas.

Pressure and liquid seals must consider the pressures in the adjacent compartments (which may be greater than in the gun compartment) and the fluids within those compartments. Temperatures within adjacent compartments must also be considered.

DRAINAGE

Provide drains for gun compartment and the equipment within. Set outlets overboard where feasible. Provide separate drains where necessary to prevent mixing of fluids. Drains should be shaped and sized to preclude trapped fluids which could freeze and prevent drainage. Position drain outlets to prevent reentry into the gun compartment or entry into other compartments. Provide for inspection to assure open drains.

6. AMMUNITION STORAGE

Design the storage area to provide ready access to the gun for feed and return. Provide for adequate purge air circulation. Review damage criteria and integrate it into the design requirements. Eliminate from the compartment all lines and components not essential to the storage and feeding of ammunition.

DESIGN NOTE 3E4 - VALIDATION TEST CRITERIA

1. INTRODUCTION

A test program which will verify that the design of the gun compartment meets the operational requirements is essential.

The purpose of the testing is twofold (1) to perform a ground test to validate the design and certify readiness for flight test, and (2) to flight-test the gun compartment under the extremes of operational environment which may be expected in service.

As a minimum, measure the following parameters:

- Time
- Temperature (ambient)
- Pressure
- Gun rate
- Gun temperature
- Number of rounds fired
- Gas constituents (H_2, CO, CH_4)
- Purge airflow
- Burning (flaming)

Verification of the analysis and design effort that has gone into developing a gun compartment can only be made by careful, methodical, and accurate testing, including ground as well as flight-test. From the onset of the program, plan a test program that will, insofar as possible, duplicate the worst possible conditions to be encountered by the aircraft gun system so that successful accomplishment of the tests will constitute design validation.

Conduct the ground tests as soon as prototype hardware can be designed and fabricated. Conduct the flight tests using flight-rated hardware when successful results are obtained from the ground tests.

Test the gun compartment insofar as possible under actual operating conditions. For the ground tests, fire the guns to the maximum possible burst

lengths. Actuate the purge system to test the ability to hold gas concentrations to acceptable limits. For the flight tests, fire the guns and actuate the purge system as in the ground tests while maneuvering the aircraft to its utmost capability.

Install the same equipment (guns, actuators, motors, valves, etc) to be used in the operational vehicle when conducting the tests. Select instrumentation which is accurate and reliable under the severe conditions expected during tests. Calibrate the system to establish and maintain a suitable baseline.

Preliminary results from the tests can provide confidence in the design so that the tests can continue into more severe regimes. They can also reveal areas which need improvement as well as danger areas which can be avoided. The final results validate the design and establish confidence in the operational capability of the gun system.

2. GUN-GAS DETECTION MEASUREMENTS

Critical to the success of the test is the ability to detect the gun-gas and measure the relative value of its constituents. Concurrently, the environmental and operating conditions must be measured to determine the effect of the gas concentration.

Select sensors that can extract samples of the air within the compartment during gun firing and provide a determination of the explosive level of constituents. The LFL of the gas mixture must be established so that the gas reading during gun firing will show the relationship between the actual level and the LFL. Results may be displayed in real-time or determined later in the laboratory by precise measuring equipment. Verify that the sensing devices can measure the mixture accurately within the time allotted and under the environmental conditions (altitude, temperature, vibration, etc). Calibrate the sensors by measuring mixtures of known certified gases. Measure the elapsed time during testing with appropriate notations for significant events. Measure ambient conditions, pressure, and temperature, in and outside the gun bay. Measure the gun rate and the number of rounds fired. Provide a means of sensing combustion within the bay. Record the results of all the sensing devices photographically and/or electronically so that a permanent account of test conditions and results can be kept.

If burning (flaming) of the gun-gases within the bay is permitted, a vent ratio (square feet of exit area divided by 100 cubic feet of volume) of five or better will restrict overpressures to approximately 5 psig. If burning is not permitted, keep the mixture below its LFL.

3. GUN COMPARTMENT AIRFLOW

Provide a flow of air to the gun compartment that will keep the gas/air mixture within the specified range. Record the intervals between the time the trigger is depressed, the purge air enters the chamber, the trigger is released, and the airflow stops. Measure the flow rate, bay temperature, and purge air temperature.

If an ejector is used to purge specific high-gas concentration areas, record the time intervals in the same way as the purge airflow entry. Record the pressure, temperature, and flow rate within the ejector, as well as pressure and temperature of the volume to be purged.

4. AMMUNITION STORAGE AIRFLOW

In many gun installations, particularly where the spent cases are returned to the storage system thus creating possible hazardous gas conditions from the smoking cases and the unexpended residue within, purge air circulation will be required within the ammunition compartment. If the purge system includes the ammunition storage compartment, test the storage compartment to the same criteria as the gun compartment.

5. FIRE DETECTION AND EXTINGUISHING

For installations where a fire-detecting instrument is required, test the ability of the instrument to detect and record the existence of fire within the bay as the gun-gas burns. Evaluate the trade-offs between a full-time detecting system and a system that is activated only during gun-firing.

If automatic fire extinguishing is desired, select a system that can distinguish between the momentary flash of burning gun-gas, and the sustained fire from other flammable sources. Ensure that the extinguishing medium is directed to the areas most susceptible to fire (for example gun breech, ammunition exit and return areas, and ammunition storage). Select a system that can provide adequate quenching within the weight and volume limitations.

6. GAS LEAKAGE SUPPRESSION AND CONTROL

Leakage of gun-gas can be hazardous to the crew because of its toxicity, as well as because of the fire and explosion potential. Install sensors to measure the amount of gas leakage into areas deemed undesirable for gas entry. Examples might be the crew compartment or a fuel storage or transfer area.

Determine the ability of the seals around the gun bay to retain the gas when the guns are fired. Test any collecting devices to determine whether gas emission is collected in the required manner. Test any enclosures to determine whether they are of the proper shape and material to withstand the heat, pressure, and corrosive gases to which they will be exposed. Examine the muzzle seal with particular care since the major part of the gas emitted from the gun is emitted from the muzzle and the slipstream tends to blow the gases back into the gun bay. Test the seal for its ability to withstand gas leakage during the forces and temperatures generated during gun firing.

APPENDIX

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